MAGNETICALLY DRIVEN ACCRETION DISK WINDS AND ULTRA-FAST OUTFLOWS IN PG 1211+143

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ABSTRACT

We present a study of X-ray ionization of MHD accretion-disk winds in an effort to constrain the physics underlying the highly ionized ultra-fast outflows (UFOs) inferred by X-ray absorbers often detected in various sub classes of Seyfert active galactic nuclei (AGNs). Our primary focus is to show that magnetically driven outflows are indeed physically plausible candidates for the observed outflows accounting for the AGN absorption properties of the present X-ray spectroscopic observations. Employing a stratified MHD wind launched across the entire AGN accretion disk, we calculate its X-ray ionization and the ensuing X-ray absorption-line spectra. Assuming an appropriately ionizing AGN spectrum, we apply our MHD winds to model the absorption features in an XMM-Newton/EPIC spectrum of the narrow-line Seyfert, PG 1211+143. We find, through identifying the detected features with Fe Kα transitions, that the absorber has a characteristic ionization parameter of $\log (\xi, [\text{erg cm s}^{-1}]) \approx 5\text{–}6$ and a column density on the order of $N_{\text{H}} \approx 10^{23} \text{cm}^{-2}$ outflowing at a characteristic velocity of $v/c \approx 0.1\text{–}0.2$ (where $c$ is the speed of light). The best-fit model favors its radial location at $r_c \approx 200 R_o$ ($R_o$ is the black hole’s innermost stable circular orbit), with an inner wind truncation radius at $R_i \approx 30 R_o$. The overall K-shell feature in the data is suggested to be dominated by Fe XXV with very little contribution from Fe XXVI and weakly ionized iron, which is in good agreement with a series of earlier analyses of the UFOs in various AGNs, including PG 1211+143.

Key words: accretion, accretion disks – galaxies: individual (PG1211+143) – galaxies: Seyfert – methods: numerical – X-rays: galaxies

1. INTRODUCTION

Blueshifted absorption lines are among the most common spectral features seen in the spectra of accreting compact objects across a large dynamic range in black hole (BH) masses, from the supermassive BHs of active galactic nuclei (AGNs) to the stellar-mass BHs of galactic binary systems. In the former case, approximately 50% of Seyferts and quasars (QSOs) exhibit absorption signatures in the UV band (e.g., Crenshaw et al. 1999) with a similar fraction (\sim 50%) of Seyfert 1s showing blueshifted absorption features in their X-ray spectra (Reynolds et al. 1997; George et al. 1998), indicative of an underlying physical link between these two outflow components. A small fraction (\sim 10%) of the radio-quiet QSOs further show substantially blueshifted UV resonance lines, referred to as BALs; these are mainly C iv/ Mg ii (high/low ionization) at velocities of $v/c \sim 0.04\text{–}0.1$, where $c$ is the speed of light (e.g., Crenshaw et al. 2003).

X-ray spectroscopy plays a fundamental role in the study of AGN absorber properties because, compared to the UV transitions, the X-ray transitions span a much wider range of the ionization parameter $\xi$ (i.e., the ratio of photon to electron fluxes); thus, within the span of 1.5 decades in photon energy ($\sim 0.3\text{–}10 \text{keV}$), one can sample atomic transitions that cover 5 decades in $\xi$ (e.g., from neutral Fe to Fe xxvi) and, presumably, a large range of physical length scales. Typically, the so-called X-ray warm absorbers (WAs) have characteristic local columns of $N_{\text{H}} \lesssim 10^{22} \text{cm}^{-2}$ and an ionization parameter in the range of $-1 \lesssim \log \xi \lesssim 4$ at line-of-sight (LOS) velocities of $v/c \lesssim 0.01$ (e.g., Reynolds & Fabian 1995), presumably originating from sub-parsec to parsec scales. A rich spectral diversity in the soft X-ray regime ($\lesssim 2\text{–}3 \text{keV}$) with a large number of ion transitions allow the statistical studies of their X-ray absorption-line properties (e.g., Behar et al. 2003). Among them, the absorption measure distribution (AMD) can be used as a global measure of the density of the radiation-absorbing gas along an LOS. The AMD is the differential hydrogen-equivalent column of $N_{\text{H}}$ per decade of $\xi$, i.e., $dN_{\text{H}}/d \log \xi$, and is computed from the measured columns of a variety of ion species of several elements spanning a large range in $\xi$ (e.g., Steenbrugg et al. 2005; Holczer et al. 2007; Behar 2009; Dettmers et al. 2011). The AMD determination in a number of radio-quiet Seyferts seems to indicate, to zeroth order, a similar global column distribution (i.e., a roughly constant AMD), implying a wind density $n(r)$ that is similar in each of them and decreases as $n(r) \propto r^{-1}$ with a radius $r$ (e.g., Dettmers et al. 2011; Holczer & Behar 2012).

Furthermore, in recent years, exhaustive X-ray studies of Fe K-shell transitions in AGNs by XMM-Newton and Suzaku have revealed the presence of another outflowing component in the Seyfert spectra, typically identified as highly ionized high-Z ions such as Fe xxv/Fe xxvi with H-equivalent columns of $N_{\text{H}} \gtrsim 10^{26} \text{cm}^{-2}$ and a high ionization parameter (log $\xi \gtrsim 4$) at near-relativistic outflow speeds of $v/c \gtrsim 0.03$, named for this reason, ultra-fast outflows (UFOs). The detected UFOs appear to be ubiquitous across both radio-quiet Seyferts like PG 1211+143 (see also Pounds et al. 2003; Pounds & Page 2006; Reeves et al. 2009; Tombesi et al. 2010a, 2011a, 2012a;
Gofford et al. 2013, 2014) and radio-loud ones (e.g., 3C 111, 3C 120, 3C 390.3, and 3C 445) with a likely association of their properties to the radio spectra (Tombesi et al. 2010b, 2011b). The higher X-ray content and increased wind ionization of the latter suggest that strong X-ray photoionization apparently does not inhibit the launch of such fast winds. A detailed study of the properties of X-ray absorbers in a sample of 23 AGNs using high-resolution X-ray spectroscopy was conducted by Blustin et al. (2005) with the conclusion that most of the X-ray absorbing matter is launched from large radii (the AGN molecular torus) with kinetic luminosities that are only a small fraction of the AGN budget. In addition to these Seyferts and nearby QSOs, optically/UV-bright BAL QSOs and their variants (e.g., non-BAL and mini-BAL QSOs) apparently show similar X-ray UFOs, but with even higher velocities, up to \(v/c \sim 0.7-0.8\) in extreme cases\(^7\) such as APM 08279 + 5255 (Chartas et al. 2002, 2003, 2007, 2009).

PG 1211+143 is a bright quasar at redshift \(z = 0.0809\) (Marziani et al. 1996) with an X-ray luminosity of \(\sim 10^{44} \text{erg s}^{-1}\) in a 2–10 keV band for an \(H_0 = 75 \text{ km s}^{-1} \text{Mpc}^{-1}\) and a Galactic hydrogen-equivalent column density of \(N_H = 2.85 \times 10^{20} \text{ cm}^{-2}\) (Murphy et al. 1996). It is an optically bright quasar with a prominent “Big Blue Bump” that results in a relatively steep optical/UV-to-X-ray flux ratio\(^8\) \((\alpha_{OX} = -1.45)\). Among other spectral features, the first XMM-Newton/EPIC/RGS observation of PG 1211+143 in 2001 revealed the first evidence of a highly ionized UFO with mass flux and kinetic energy comparable to that of the mass accretion rate and bolometric luminosity, respectively (Pounds et al. 2003; Pounds & Reeves 2009), although we note that others have reached different conclusions depending on how the baseline continua are treated (Kaspi & Behar 2006; Gallo & Fabian 2013; Zoghbi et al. 2015). Their analyses detected several strong absorption features identified as blueshifted K \(\alpha\) transitions of C, N, O, Ne, Mg, S, and Fe. The properties of the Fe feature, in particular, imply a wind column density of \(N_{\text{Fe}} \sim 5 \times 10^{23} \text{ cm}^{-2}\) at velocity \(v/c \sim 0.08\) and an ionization parameter of \(\log \xi \sim 3.4\). A second observation of PG 1211+143 with XMM-Newton/EPIC/RGS in 2004 (Pounds & Reeves 2007) and in 2007 (Pounds & Reeves 2009) again detected similar UFOs, implying their persistent presence despite their highly variable X-ray spectra. A more detailed spectral analysis of such outflows has been recently performed using the XMM-Newton data (e.g., Tombesi et al. 2010a, 2011a; Pounds 2014) to confirm their presence, which is in agreement with the earlier results. Finally, a more recent observation with Suzaku/XIS has also revealed the same UFOs (Reeves et al. 2008; Patrick et al. 2012; Gofford et al. 2013).

Despite the long-known UV/X-ray WAs and an increasing number of statistically significant detections of the X-ray UFOs, the detailed geometrical structure of these ionized winds, including the formation and acceleration processes, are poorly constrained to date. Yet, each of these issues is crucial to the comprehensive picture of the accretion-powered phenomena in accretion/outflow physics. Plausible launching mechanisms for general outflows include radiation-driven (e.g., Proga et al. 2000; Proga & Kallman 2004; Nomura et al. 2013, in the context of UV BALs in luminous QSOs), thermally driven (e.g., Begelman et al. 1983), and magnetically driven (e.g., Blandford & Payne 1982; Königl & Kartje 1994; Contopoulos & Lovelace 1994, hereafter CL94; Ferreira 1997; Fukumura et al. 2010a, 2010b, 2014 hereafter FKCB10a, FKCB10b, F14). There have also been hybrid models (e.g., Proga 2003; Everett 2005; Ohsuga et al. 2009; Ohsuga & Mineshige 2011) that have attempted to explain an AGN phenomenology associated with inflow and outflow.\(^9\) With increasingly improved fully numerical schemes, various extensive simulations have been made in the context of the disk-wind scenario for the (i) magnetically driven (e.g., Fendt 2006; Pudritz et al. 2006; Murphy et al. 2010; Porth & Fendt 2010; Stepanovs & Fendt 2014; Stute et al. 2014) and (ii) radiation-driven launching mechanisms (e.g., Proga & Kallman 2004; Nomura et al. 2013; Higginbottom et al. 2014; Hagino et al. 2015). Although the acceleration mechanism(s) of the observed winds remain uncertain, the magnetic origin seems to be favored over the radiation pressure origin according to the latest time-dependent hydrodynamic simulations with multi-dimensional Monte Carlo calculations for radiative transfer (e.g., Higginbottom et al. 2014, but also see Hagino et al. 2015) and UV/X-ray observations (e.g., Everett 2005; Kraemer et al. 2005; Crenshaw & Kraemer 2007). This may also be the case for Galactic binaries (e.g., Miller et al. 2006, 2008; King et al. 2012, 2014). One should note that certain phenomenological outflow models, with an emphasis on individual spectral features such as the Fe K-shell transitions, are able to reproduce the properties of certain prominent transitions such as their EW and their LOS velocity (e.g., Sim 2005; Sim et al. 2008, 2010; Tatum et al. 2012), however, without providing a global dynamic wind perspective.

To the best of our knowledge, none of the existing wind models, whether semi-analytic or numerical, have been able to deliver a practical prescription for the observed X-ray absorption features, i.e., local properties (like column, ionization state, or velocity) of the WAs and UFOs together with a global picture of the outflow physics (i.e., density/ionization structure from smaller scales to larger scales and geometrical properties as a whole). From a methodological viewpoint, most models fit the properties of the specific features, i.e., column and velocity, implementing xspec/xstar to obtain the ionization parameter, and obtaining the velocity of the plasma associated with specific transitions with little concern about how these fit within a global model of the AGN outflows.

The spirit of our recent works (i.e., CL94; FKCB10a; FKCB10b; Kazanas et al. 2012; F14) has been exactly the opposite, in that we begin with a global MHD wind model and use the X-ray spectroscopic observations to determine the global properties of these winds. In this paper we employ a similar philosophy in an attempt to model the observed Fe xxv/UFO in PG 1211+143 within the context of the well-defined MHD-driven wind models referred to above. This study allows us to explicitly constrain some of the defining MHD wind parameters in the spirit of a model-driven approach. Our deeper goal is to gain a better understanding

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\(^7\) While the winds of the typical high-velocity UV transition (\(L_O, C\gamma, \text{ etc.}\)) BALs may be driven by line radiation pressure, it is a challenge for this scenario to accelerate the highly ionized near-relativistic X-ray UFOs.

\(^8\) The spectral index \(\alpha_{OX} \equiv 0.384 \log(f_{2\text{keV}}/f_{5000})\) measures the X-ray-to-UV relative brightness where \(f_{2\text{keV}}\) and \(f_{5000}\) are, respectively, 2 keV and 5000 Å flux densities (Tananbaum et al. 1979).

\(^9\) The derived values of large \(\xi, N_H, \text{ and } v\) of certain X-ray UFOs presumably originating from smaller radii are a serious challenge to the line-driven and thermally driven scenarios.
of the underlying physical structure of the observed winds from a global standpoint. Within this framework, WA and UFO features are generically identified as belonging to the same wind structure that spans the entire domain of the AGN accretion disk. We briefly describe the essence of the MHD-driven winds in Section 2 along with our methodology for constructing a grid of simulated line spectra for subsequent data analysis. In Section 3 we show our preliminary results based on a 60 ks XMM-Newton/EPIC spectrum of PG 1211+143, deriving the best-fit values for the primary model variables. We summarize and discuss the implications of the model in Section 4.

2. ULTRA-FAST OUTFLOWS IN STRATIFIED MAGNETOHYDRODYNAMIC DISK WINDS

2.1. The Magnetized Disk-wind Structure

Following FKCB10a and FKCB10b for the computational prescription of magnetically driven disk-wind models under steady-state axisymmetric conditions, we seek new insight into their structure from the observational data. We apply our model assuming the observed X-ray UFO signatures in AGNs (i.e., Fe xxv/Fe xxvi resonance transitions)\(^{10}\) are produced by X-ray photoionization of MHD winds launched off of an accretion disk. The detailed characteristics of the model discussed in FKCB10a and FKCB10b will be briefly described here. Geometric and physical properties of the wind in the model are primarily governed by two conserved quantities along a wind streamline, namely the particle-to-magnetic flux ratio \(F_o\) and the angular momentum \(H_o\). The former, \(F_o\), predominantly determines the wind kinematics and the latter, \(H_o\), generally dictates the global wind structure in the poloidal plane. The fundamental quantity of axisymmetric MHD is the magnetic stream function \(\Psi(r, \theta)\), assumed to have a self-similar form \(\Psi(r, \theta) = (R/R_o)^{1/2} \Psi(\theta) \Psi_o\), with \(\Psi_o\) as the poloidal magnetic flux through the fiducial innermost disk radius at \(R = R_o\). \(\Psi(\theta)\) is its angular dependence to be solved for, and \(q\) is a free parameter that determines the radial dependence of the poloidal current. The scalings of the poloidal magnetic stream function carry over to the rest of the wind properties, of which we show only the magnetic field, velocity, and density

\[
B(r, \theta) \equiv (R/R_o)^{\gamma - 2} B(\theta) B_o,
\]

\[
r(r, \theta) \equiv (R/R_o)^{1 - 2/\gamma} \nu(\theta) v_o,
\]

\[
n(r, \theta) \equiv (R/R_o) \frac{2 \gamma - 3}{\gamma} \bar{n}(\theta) B_o^2 v_o^{-2} m_p^{-1},
\]

respectively, with the momentum balance equation

\[
\rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \rho - \rho \nabla \Phi + \frac{1}{c} (\mathbf{J} \times \mathbf{B}),
\]

where \(m_p\) is the proton mass and \(\rho\) is the plasma mass density. The dimensionless angular functions denoted by a tilde (\(\sim\)) must be obtained from the conservation equations and the solution of the Grad–Shafranov equation (the force balance equation in the \(\theta\)-direction) with the initial values on the disk (denoted by the subscript \(\sim\)) at \((R = R_o, \theta = 90^\circ)\). The density normalization at \((R_o, 90^\circ)\), setting \(\bar{n}(90^\circ) = 1\), is given in terms of the dimensionless mass accretion rate \(m_\alpha\)

(normalized to the Eddington accretion rate \(M_E = L_E/c^2\); see FKCB10a) by

\[
n_o \equiv \frac{\tau (\dot{m}_\alpha) f_o}{\sigma_T R_S},
\]

where \(\sigma_T\) is the Thomson cross-section, \(f_o\) is the ratio of the outflow rate in the wind to \(\dot{m}_\alpha\), and \(R_S\) is assumed to be on the order of the Schwarzschild radius \(R_S\). The Thomson depth \(\tau (\dot{m}_\alpha)\) of the plasma at the innermost disk radius is further scaled by the dimensionless mass accretion rate \(\dot{m}_\alpha\) with normalization \(\tau_o\), as \(\tau (\dot{m}_\alpha) \equiv m_\alpha \tau_o\), which leads to

\[
n_o \equiv \frac{f_o \dot{m}_\alpha}{\sigma_T R_S} = 5 \left( \frac{f_o \dot{m}_\alpha}{M_8} \right) \times 10^{11} \text{cm}^{-3}.
\]

where we have introduced an effective mass accretion rate of \(\dot{m}_\alpha, o\) as it is difficult to decouple one from the other from observations alone. In this paper we consider one of the fiducial wind solutions, model (A), from Fukumura et al. (2014), as a baseline wind model by choosing \(q = 0.93\) (i.e., \(n \propto r^{-1.14}\)), \(f_o = 1\), and \(\tau = 10\) representing an optically thick disk of \(\dot{m}_\alpha, o = 10\) at \(R = R_S\) (lowercase \(r\) denotes the radial distance in 3 space, while \(R\) is the radial distance along the disk surface). Here, we only highlight the essence of the model; details can be found elsewhere (CL94; FKCB10a,b; Kazanas et al. 2012; F14). Formally the self-similar winds extend from \(r = 0\) to \(r \to \infty\); however, physical considerations restrict these to a finite, but broad, range in \(r\), so we choose the dimensionless factors \(f_i\) and \(f_r\) to denote the inner and outer truncation radii, respectively, of our winds on the disk surface by

\[
R_i \equiv f_i R_S, \quad R_T \equiv f_r R_S
\]

where the value of \(f_i\) is to be constrained by the X-ray data while \(f_r \gg 1\), typically \(\sim 10^2\). Once launched, the asymptotic wind speed in this solution is found to be \(v_p/v_o \sim 4\) at \(r/R_S \lesssim 10^3\) (see F14 for details).

2.2. Photoionization of Disk Winds

With the dimensionless mass-invariant wind structure for a given \(m_\alpha, o\) and a viewing angle \(\theta\), the only significant difference in the wind ionization properties across objects of different luminosities comes from the spectral energy distribution (SED) of the accretion-powered luminosity \(L \equiv m_\alpha L_E\epsilon\) where \(L_E = 1.25 \times 10^{39} \text{ erg s}^{-1}\) is the Eddington luminosity with \(M_8\) as the BH mass in units of \(10^8 \text{ M}_\odot\) and \(\epsilon \approx 0.1\) is the accretion efficiency. In FKCB10a we used a simple power-law spectrum of the form \(F_\nu \propto \nu^{-1}\) (e.g., Sim et al. 2008, 2010) and in this paper we consider a multi-component SED consisting of a multicolor disk (MCD) with an innermost temperature of \(kT_{bb}\) and an X-ray power-law of photon index \(\Gamma\) (with a low-energy cut-off at 50 eV and a high-energy turnover at 200 keV) normalized to the MCD by \(a_\odot\) (e.g., Everett 2005; Sim 2005), a more appropriate SED for bright Seyferts such as PG 1211+143. The ionizing luminosity (X-ray plus EUV) is then \(L_{ion} \approx 0.1 L \approx 1.25 M_8 \times 10^{44} \text{ erg s}^{-1}\) for a relatively high accretion rate of \(m_\alpha = 1\), as suggested in earlier analyses (e.g., Pounds et al. 2003).

\(^{10}\) The model, however, is not restricted to Fe K-shell transitions and can be extended in general to include other ionic features detected in AGNs and BH binaries.
For a characteristic Seyfert SED, we set $\Gamma = 2$ (see Figure 5 in Tombesi et al. 2011a for a homogeneous sample of 42 radio-quiet AGNs; Pounds & Reeves 2009) and $\alpha_{\text{OX}} = -1.5$ (adopted from NED: NASA/IPAC Extragalactic Database and Blustin et al. 2005) while leaving an inclination angle $\theta$ and the disk temperature $kT_{\text{bb}}$ as free parameters to be determined by PG 1211+143 UFO observations (e.g., Pounds et al. 2003; Tombesi et al. 2011a). It should be noted that, in agreement with FKCB10b, Blustin et al. 2005 found that only more negative values of $\alpha_{\text{OX}}$ allow higher velocity absorbers (i.e., $v_{\text{out}} \gtrsim 10,000 \text{ km s}^{-1}$) based on their analysis of phenomenological and physical properties of the detected WAs using high-resolution X-ray spectroscopy of a sample of Seyfert 1 AGNs.

Given the wind density normalization $n_0$ through $n_\perp$, the photoionization balance is computed radially outward employing xstar (Kallman & Bautista 2001, v2.2.1bn13) by setting the SED of Figure 1(a) as the ionizing spectrum at the innermost radius; the radiation transport in the wind is done by discretizing the radial wind coordinate using a large number of cells in the radial direction for a given angle $\theta$ (typically with $\Delta r/r \sim 0.1$, allowing us to treat each radial cell as a plane, yielding 50–70 radial zones; see FKCB10a). We apply xstar in the first zone to compute the ionization equilibrium of the plasma and its opacity and emissivity. We then use the output of this zone as the input for the next and continue to the outer edge of the wind along a given LOS (i.e., a given $\theta$). We calculate the absorption spectra with the Voigt function (e.g., Mihalas 1978; Kotani et al. 2000; Hanke et al. 2009), defined as

$$H(a, u) \equiv \frac{a}{\pi} \int_{-\infty}^{\infty} \frac{e^{-y^2} dy}{(u-y)^2 + a^2},$$

where we use $a \equiv \Gamma_E / (4 \pi \Delta \nu_D)$ with $\Gamma_E$ being the Einstein coefficient and $\Delta \nu_D$ the line Doppler broadening factor. The dimensionless frequency spread about the transition frequency $\nu_0$ is given by $u \equiv (\nu - \nu_0) / \Delta \nu_D$. Note that in order to compute the flux in lines whose thermal width is narrower than the computational frequency grid (especially in cases of multiple lines within a given frequency spacing), the parameter $v_{\text{turb}}$ (typically $\sim 1000 \text{ km } \text{s}^{-1}$) of xstar is employed to provide a line width $\Delta \nu_D$ that is consistent with the produced flux over the grid size. However, our wind model instead provides a well-defined velocity shear $\Delta V$ with a corresponding radial velocity difference $\Delta v_D$ between two adjacent radial cells; we employ this velocity instead of $v_{\text{turb}}$ to define an equivalent $\Delta \nu_D = \nu_0 (v_{\text{turb}} c) \Delta v_D$, a value consistent with the underlying wind kinematics (see FKCB10a for a detailed numerical prescription).

Using the ionic column $N_{\text{ion}}(r; \theta)$ over a radial cell of width $\Delta r$ as a function of ionization parameter $\xi(r; \theta)$ obtained with xstar under ionization and heating–cooling balance, we can compute the wind opacity $\tau_{\xi}(r, \theta)$ of any given photon energy at any given point with wind velocity $v(r; \theta)$ given from the relation

$$\tau_{\xi}(r, \theta) = \sigma_{\text{photo,}\xi}(r, \theta) N_{\text{ion}}(r, \theta),$$
where the line photoabsorption cross-section $\sigma_{\text{photo},\nu}$ at frequency $\nu$ is given by

$$\sigma_{\text{photo},\nu} = 0.001495 \frac{f_{ij} H(a, u)}{\Delta \nu D} \text{cm}^2,$$

(10)

and $f_{ij}$ is the oscillator strength of the transition between the $i$th and $j$th levels of an ionic species. Finally, we construct a two-dimensional grid of the baseline spectra for $\theta \in [30^\circ, 70^\circ]$ and $kT_{\text{bb}} \in [10 \text{ eV}, 70 \text{ eV}]$ for density normalization $n_0 = 5.1 \times 10^{11} \text{ cm}^{-3}$ ($\bar{m}_{a,o} = 10$). Here we introduce the quantity $N_{\text{H}}$, defined as the number density of Fe XXV ions divided by the Fe abundance and multiplied by the width of our local radial grid size $\Delta r$. Some of the calculated $N_{\text{H}}$ values (assuming solar abundances) for four sets of $\theta$ and $kT_{\text{bb}}$ are shown as a function of the wind velocity $v/c$ in Figure 1(b). Considering this figure, it is noted that the velocity decreases with increasing distance $r$ and decreasing ionization parameter $\xi$ for a given LOS angle $\theta$. The reader should note that $N_{\text{H}}$ does not depend monotonically on velocity because at small $r$ (and high $v$) a good fraction of Fe is fully ionized, while at larger $r$ (and low $v$) the Fe ionization drops precipitously. Finally, the total $N_{\text{H}}$ and $N_{\text{H}}$ (Fe xxv) are found by integrating $N_{\text{H}}$ over $r$ along a given LOS. As seen, for a given $\bar{m}_{a,o}$, the normalization of the LOS column depends primarily on the inclination angle $\theta$, while the location of the peak $N_{\text{H}}$ (i.e., where $N_{\text{H}}$ is maximum), for a given $\alpha_{\text{OX}}$ and $n_{\text{so}}$, is mainly determined by the disk temperature $kT_{\text{bb}}$. Such a correlation is also discussed in FKCB10b.

### 3. PRELIMINARY COMPARISON WITH THE PG 1211+143 DATA

#### 3.1. XMM-Newton/EPIC Data

We use an XMM-Newton spectrum of PG 1211+143 (obsID: 0112610101) obtained with the EPIC-pn camera for an approximately 60 ks duration on 2001 June 15 (Pounds et al. 2003), for which a detailed data reduction procedure and observed spectral and temporal features of this object can be found elsewhere (e.g., Pounds et al. 2003; Kaspi & Behar 2006; Pounds & Page 2006; Bachev et al. 2009; Pounds & Reeves 2009; Tombesi et al. 2011a; Gallo & Fabian 2013; Pounds 2014, and references therein). Earlier analyses of the UFOs, typically identified as either Fe xxv and/or Fe xxvi, seem to imply an estimate on the column density of $N_{\text{H}} \sim 10^{23} \text{ cm}^{-2}$, velocity of $v/c \sim 0.1-0.15$, and ionization parameter of $\log \xi \sim 3-5$, although an alternative view may also be...
conceivable claiming that the observed Fe K absorption feature can be attributed to several consecutive low charge states of Fe (see, e.g., Kaspi & Behar 2006).

3.2. Spectral Modeling for the Fe Kα UFO

Here we perform a spectral analysis of the UFOs previously detected in the 60 ks XMM-Newton/EPIC spectrum of PG 1211 +143 (e.g., Pounds et al. 2003; Pounds & Reeves 2009; Tombesi et al. 2011a). Focusing on the hard X-ray absorption feature identified in the data as an Fe K-shell resonance transition, we implement our MHD wind model, mhdwind, into xspec as a multiplicative table model as discussed in Section 2. We follow the analysis procedure in Tombesi et al. (2011a) where the 2–10 keV band is modeled with an underlying continuum power law (po). To fit the Fe Kα absorber, however, we replace the phenomenological xstar component with mhdwind. The symbolic spectral form reads "phabs*(po+zga)\text{mtable[mhdwind]}" where we have used the previously estimated values of the parameters, Galactic absorption due to neutral hydrogen column (phabs) \(N_H = 2.85 \times 10^{20} \text{cm}^{-2}\) (Murphy et al. 1996), \(\Gamma = 2\) (Tombesi et al. 2011a), and BH mass, \(M = 10^8 M_\odot\) based on the earlier estimates (Kaspi et al. 2000; Bentz et al. 2009). Attributing the pronounced emission line at \(\sim 6.5\) keV (in the rest-frame) to fluorescence from the disk, our mhdwind is constrained simultaneously with a redshifted gaussian component zga of XSPEC in which the line width is set to \(\sigma_{\text{Fe}} = 0.15\) keV, whose exact value has little influence on our end results.

We explore two cases by simultaneously considering both the Fe XXV and Fe XXVI transitions; model (A), where \(R_c\), the innermost radial extent of the wind at \(\theta = 90^\circ\), is equal to \(R_o\), \(\simeq R_S\) and model (B), where this restriction is relaxed. Figure 4(a) shows the best fit for each model (A) and model (B) in comparison with the no mhdwind model. We set \(n_o = 5 \times 10^{14} \text{cm}^{-3}\) \((m_a = 10)\) while varying \(\theta, kT_{\text{bb}}\), and \(f_t\). The best-fit values are listed in Table 2. We used different values of \(n_o\) in our calculations, but its effective role is to slightly change the trough depth. In the current wind model, both visual and statistical inspection favors model (B) by \(\Delta \chi^2 = 2.3\) (Table 2) in which the wind does not originate at the fiducial radius \(R_o\) on the disk surface, but at \(R_I = f_IR_S\) with \(f_I > 1\).

In model (A), where \(f_I = 1\) is assumed, we obtain our best fit for values \(\theta = 40^\circ\) (pegged) and \(kT_{\text{bb}} = 30\text{ eV}\) with \(\chi^2/\nu = 200.84/129\) with mhdwind, which is a statistically significant additional to the continuum (with an improvement of \(\Delta \chi^2 = 34.1\) for two additional parameters). In model (B) we relaxed the restriction on the wind truncation radius of \(f_I = 1\) in model (A). Table 3 shows a list of various characteristic radii in this model. Our analysis yields a best-fit model with \(\theta = 50^\circ\), \(kT_{\text{bb}} = 38\text{ eV}\), and \(f_I = 10^{14}\), as shown in Figure 4(a) and Table 2, where we obtain \(\chi^2/\nu = 198.54/128\), which is more significant in comparison with model (A). We note that the model spectrum now has a sharper edge on the bluer side of the feature, as required by the data. The total column \(N_H = 1.2 \times 10^{23} \text{cm}^{-2}\) from model (B) is comparable to the previous estimate with the xstar model, although our wind is continuous rather than discrete.

As a measure of assessing the Fe XXV absorption wind properties we first calculate a characteristic radius \(R_c\) at which the wind photoelectric absorption column for the Fe xxv transition becomes maximum for a given LOS inclination angle \(\theta\). At this radius we compute the other physical quantities listed in Table 2. Note that the total \(N_H\) (in units of \(10^{22} \text{cm}^{-2}\)) is defined as the local column density integrated over the LOS distance.

Along the LOS for the values of \(\theta\) obtained by our fits (see Table 2), the wind is both Thomson thin and also thin at the Fe energies. As argued earlier, because the Fe xxv/Fe xxvi line opacities are non-monotonic functions of the radial coordinates in these directions, we define a radius \(r_c\) along each of these LOSs at which the line(s) opacity(ies) is (are) maximized (given by the entry \(\tau_{\text{max}}\) of Table 2). In fact, these coincide with the maxima of \(N_H\) of Figure 1(b). Because of the smoothness and continuity of \(N_H\) with \(r, \xi\), or \(\nu\), the absorption of X-ray photons begins at \(r < r_c\) and extends across more than one decade in radius; hence, one should bear in mind that a given absorption feature in our models does not correspond to a specific unique wind component.

In order to examine the multi-parameter space spanned by \((\theta, kT_{\text{bb}})\) in more detail we interpolate the wind variables such as velocity \(v_c\) and characteristic radius \(R_c\) as shown in Figure 4(b), where the color shows the total column \(\log(N_H[\text{cm}^{-2}\])\) for Fe xxv with contours of the radius log\((r_c/R_o)\) (solid), and the contours of \(v_c/l\) (dashed). The best-fit model (B) for Fe xxv is indicated by a dark dot. One should keep in mind that the best-fit characteristic values (i.e., \(r_c, v_c, \xi\)) are simply constrained at the most opaque radius \(\tau_{\text{max}} = \tau (r = r_c)\) of the absorber. The neighboring plasma at \(r \lesssim r_c\) (i.e., \(v \lesssim v_c\)) also contributes progressively to the formation of the absorption feature, thus there is no single wind velocity nor column density in our model. This is a characteristic feature of the continuous wind model, which is fundamentally different from a single-component absorber model often employed in a phenomenological analysis. The corresponding confidence contours for model (B) are shown in Figure 5 where the primary variables \(\theta, kT_{\text{bb}}\), and \(f_I\) are constrained.

In the context of the current model, the best-fit model (B) is spatially identified as illustrated in Figure 6(a) where the calculated fiducial wind structure in the vicinity of the BH is superimposed, showing the normalized number density \(n(r, \theta)\) (in color), the velocity field (white arrows), the magnetic field lines (solid thick lines), the contours for density (dashed lines), and the Alfvén surface (white line). In this simplified approach a geometrically thin disk is situated in the equatorial plane at \(\theta = \pi/2\). As discussed earlier, the faster portion of the modeled Fe xxv/Fe xxvi absorber (i.e., the bluer side of the trough) and the slower one (i.e., the redder side) are respectively located at \(r < r_c\) and \(r > r_c\) along each LOS, and each progressively contributes to produce the observed absorption feature (both in depth and width).

In terms of the energy budget of the observed UFO, using the outflow density profile with \(n \propto 1/r\) (actually \(n \propto 1/r^{1.14}\) in
the present model) in this work for a supermassive BH mass of $M = M_\odot$ (Kaspi et al. 2000; Peterson et al. 2004), a mass outflow rate associated with the Fe xxv line can be estimated as

$$M_{\text{out}}(\text{Fe xxv}) \equiv 2\pi b m_p \int_0^{200} n(r, \theta) v_c(r, \theta) r dr,$$

$$\sim 4\pi b m_p n_o c R_S v_{\text{Fe xxv}} X_{\text{Fe xxv}}^{1/2}$$

and

$$\sim 2.56 M_\odot \text{yr}^{-1} \left( \frac{b}{0.4} \right) \left( \frac{n_o}{5 \times 10^{11}} \right) \times \left( \frac{M}{10^8 M_\odot} \right) \left( \frac{v_{\text{Fe xxv}}}{0.1} \right) \left( \frac{X_{\text{Fe xxv}}}{200} \right)^{1/2},$$

where $x \equiv r/R_S$ and the upper limit of integration is indicative of the distance to the Fe xxv location; i.e., $r_c = r_{\text{Fe xxv}}$ (see Table 2). This value is consistent with the earlier estimate of $\sim 3 M_\odot \text{yr}^{-1}$ (Pounds et al. 2003; Pounds & Page 2006). Since the corresponding local mechanical power is given by

$$E_{\text{out}}(\text{local}) \equiv \dot{M}_{\text{out}}(\text{Fe xxv}) v_{\text{Fe xxv}}^2 \propto r^{-1/2},$$

the local kinetic power of the Fe xxv outflow is dominated by the inner outflow radius $R_c$ yielding

$$E_{\text{out}}(\text{Fe xxv}) \sim \frac{1}{2} M_{\text{out}}(\text{Fe xxv}) v_{\text{Fe xxv}}^2$$

$$\sim 2 \times 10^{44} \text{erg s}^{-1},$$

a value comparable to the power of the observed X-ray luminosity $\sim 10^{44} \text{erg s}^{-1}$ (Pounds et al. 2003), also potentially providing a large impact on the AGN feedback process at large scales (e.g., Crenshaw & Kraemer 2012). A similarly large outflow power has been made, for example, to other bright AGNs such as PDS 456 (Reeves et al. 2003; Nardini et al. 2015).

4. SUMMARY AND DISCUSSION

We have demonstrated, by modeling its XMM-Newton spectrum, that MHD-driven winds with $n \propto r^{-\alpha}$, $\alpha \approx 1$, originally proposed to account for the X-ray WAs in Seyferts, can also encompass the UFOs, i.e., the high-velocity X-ray absorbers of the bright Seyfert PG 1211+143. The
absorber’s properties of PG 1211+143, as manifested by the Fe XXV/Fe XXVI transition properties, are determined mainly by the wind mass flux \( \dot{m}_{\text{w}} \), the disk temperature \( kT_{\text{bb}} \), and the observer’s viewing angle \( \theta \). By producing a grid of model K-shell Fe absorption lines appropriate to photoionized MHD winds, we found the that the absorber’s physical conditions are well constrained by our models. Thus, the FeXXV and FeXXVI properties are respectively given by the location of maximum opacity at \( r_i = R_{\text{in}} \approx 10^{14} \) and \( \theta_i = kT_{\text{bb}} \approx 0.208 \), ionization parameter \( \log \xi = 5.31 \) and \( 5.80 \), and the total H-equivalent columns \( \chi_0 = 1.21 \times 10^{23} \) and \( 1.67 \times 10^{23} \), with the wind truncated at radius \( f_i \approx R_i / R_S = 10^{14.48} \approx 30 \). While the best-fit values of these parameters are roughly consistent with the earlier analysis (e.g., Gofford et al. 2013), our model can further provide a geometrical and physical identification of the UFO in PG 1211+143 that is consistent with our MHD-driven view discussed for PG 1211+143.

Although in this paper we focused on the origin of the detected Fe K\( \alpha \) UFOs, our model winds extend over a large range in \( r, \xi \), and \( v \). As such, they imply the presence of other charged states that contribute to the Fe K\( \alpha \) transition by including Fe XVIII–Fe XXIV. We found that if these additional states had been included in our analysis the Fe K\( \alpha \) feature would have been much broader than seen in the data. Given our fits of Figure 4(a) and Table 2, one must surmise that the effective contribution to the 1s–2p transition from Fe XVIII through Fe XXIV in the data ought to be very small (if any). There are a number of remedies. (i) It is conceivable that the intrinsically broad absorption feature due to ionized iron at all charge states could be externally filled by scattered resonant line photons which would suppress its otherwise broader signature. Any continuous wind model will inevitably come across this issue of the contribution of states other than highly ionized (e.g., H/He-like) ones. (ii) The radial wind density
profile might be steep enough to suppress the ionic column at large distances. On the other hand, this solution may not be consistent with the observed slow absorbers (i.e., WAs) since they originate from large distances in this model. (iii) It is also probable that the fast absorbers (i.e., UFOs) could be a collection of discrete (small) gas clouds along the LOS instead of a large-scale continuous flow (e.g., Misawa et al. 2014) that might also be in a constant pressure equilibrium causing the suggested thermal instability (e.g., Holczer et al. 2007). While we note this long standing question, this is beyond the scope of our current study.

To compute the spectra of a truncated wind we simply removed from the line feature the contribution of the self-similar section of the wind that originates at $R < f_{\ell} R_5$. We also repeated the photoionization of a wind for which this section has already been removed, always assuming that the ionizing source is located at $r = 0$. This second calculation produced similar results with slightly smaller values for $\chi_\text{HI}$ because of the slightly larger flux of ionizing radiation at the values of $\theta$ considered. This could be ameliorated by a slight increase in the value of $n_{\text{w}}$. The constrained truncation radius $R_{t} \approx 30 R_5$ in Table 2 is statistically favored in the context of our MHD wind model, particularly so as to suppress the blue tail of the absorption feature. On the other hand, Giustini & Proga (2012), for example, have considered a thermally driven wind based on the model of Luketic et al. (2010). They found a relatively sharp blue edge of the line profile without truncation due to non-monotonic profiles for wind streamlines and opacity along an LOS. This implies that a complex geometry of the wind also needs to be further explored by extending the model beyond the self-similar limit.

It is suggested from a long Suzaku observation that a similar fast X-ray absorber (by iron K-shell transition at an implied outflow velocity of $v \sim 0.25c$) in PDS 456 exhibits rapid variability as short as $\sim 1$ week (Gofford et al. 2014). Their estimate of the absorber’s location in PDS 456 ($r/R_5 \sim 100–1800$) is very similar to our estimate of $r_c$ in PG 1211+143. The current steady-state model is not appropriate for treating such a time variability in its absorption features, but it is conceivable that the observed variable nature may be associated with the change in wind density (perhaps resulting from the change in mass-loading) and/or changing streamline configurations due to the variable magnetic fields. While the model is in good agreement with the data, there appear to be additional weak (intrinsic) absorbers at higher energies ($\sim 8–9$ keV). These weak absorption structures could be due to the resonance series converging to the Fe XXV edge (e.g., Kallman et al. 2004; Tombesi et al. 2011a). There could also be some contamination due to the presence of the background (instrumental) emission lines such as Cu K$\alpha$ at 8 keV in the EPIC-pn spectrum.

In this paper we employed a well-studied semi-analytic wind model as a primary component. We feel that despite their simplicity, such models should not be dismissed offhand compared to large-scale purely numerical simulations for a number of reasons: First, even today’s state-of-the-art simulations have not yet provided the practical and direct observables addressed in this paper at an observationally relevant level. Second, it is still extremely computationally challenging to self-consistently include the multi-scale multi-dimensional radiative transfer for plasma/atomic physics necessary to simulate the kind of transitions seen in UV/X-ray data while simultaneously covering a large spatial scale (i.e., ranging from 10 Schwarzschild radii all the way out to parsec scale) without suffering from numerical instability and boundary condition susceptibility. In future research, a more self-consistent disk-wind morphology needs to be considered by constructing a sophisticated (perhaps dynamical) model (e.g., Ohsuga et al. 2009; Ohsuga & Mineshige 2011), also incorporating detailed radiative transfer for spectral lines (e.g., Kallman et al. 2004; Garcia et al. 2013).

In this preliminary calculation we assumed $n_{\text{w},0} = 1$, corresponding to the density of matter on the disk surface $n_{\text{w}} = 5 \times 10^{11}$ cm$^{-3}$. We used slightly different values for $n_{\text{w}}$ and noted their weak influence in the end results. We note that our assumed value is slightly higher than the fiducial AGN value of $10^{10}$ cm$^{-3}$ (e.g., Crenshaw et al. 2003; Tombesi et al. 2011a; Gofford et al. 2013, and references therein), but its possible range can be considered as broad as $10^{8} \lesssim n_{\text{w}} \lesssim 10^{17}$ cm$^{-3}$ (e.g., Laor & Netzer 1989; George & Fabian 1991; Garcia et al. 2013) and an accurate assessment requires a more realistic modeling of accretion disk physics and its response to the photoionization process.

The present analysis is based on a selected fiducial wind structure that we have examined in our earlier work (F14). Within the three-parameter model spanned by $\theta$, $kT_{\text{b}}$, and $R_{t}$ in this paper, we do not notice degeneracy in the best-fit spectrum. Considering a complexity of magnetized disk-wind physics, however, it is conceivable that we may find another best-fit solution from slightly different wind conditions. Removing such potential degeneracy is in principle challenging since there is little a priori knowledge (at least observationally) of the underlying wind structure. Nonetheless, it will be possible to rule out some of the degenerate wind solutions by further including multiple ions of different charge states both at soft X-ray transitions (below 3–4 keV) and Fe–K$\alpha$ transitions simultaneously since all these absorption signatures should be coupled in the context of our continuous disk-wind scenario. We thus plan to extend the current preliminary model to include the soft X-ray WAs to examine a coherent predictability of the model using those AGNs exhibiting both WAs and UFOs.

We anticipate upcoming missions such as Astro-H and Athena to significantly contribute to this goal by providing more detail on the Fe–K component of the wind, as well as soft X-ray absorbers, and thus further clarify our picture of AGN structure.

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