Variable Nature of Magnetically Driven Ultra-fast Outflows

Keigo Fukumura1, Demosthenes Kazanas2, Chris Shrade2,3, Ehud Behar4,
Francesco Tombesi2,5,6, and Ioannis Contopoulos7

1 Department of Physics and Astronomy, James Madison University, Harrisonburg, VA 22807, USA; fidemi@jmu.edu
2 Astrophysics Science Division, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
3 Catholic University of America, Washington, DC 20064, USA
4Department of Physics, Technion, Haifa 32000, Israel
5 Department of Astronomy and CRESST, University of Maryland, College Park, MD 20742, USA
6 Department of Physics, University of Rome “Tor Vergata,” Via della Ricerca Scientifica 1, I-00133 Rome, Italy
7 Research Center for Astronomy, Academy of Athens, Athens 11527, Greece

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Abstract

Among a number of active galactic nuclei that drive ionized outflows in X-rays, a low-redshift \( (z = 0.184) \) quasar, PDS 456, is long known to exhibit one of the exemplary ultra-fast outflows (UFOs). However, the physical process of acceleration mechanisms is yet to be definitively constrained. In this work, we model the variations of the Fe K UFO properties in PDS 456 over many epochs in X-ray observations in the context of magnetohydrodynamic (MHD) accretion disk winds employed in our earlier studies of similar X-ray absorbers. We applied the model to the 2013/2014 XMM-Newton/NuSTAR spectra to determine the UFO’s condition; namely, velocity, ionization parameter, column density, and equivalent width (EW). Under some provisions on the dependence of X-ray luminosity on the accretion rate applicable to near-Eddington state, our photoionization calculations, coupled to a 2.5-dimensional MHD-driven wind model, can further reproduce the observed correlations of the UFO velocity and the anticorrelation of its EW with the X-ray strength of PDS 456. This work demonstrates that UFOs, even without radiative pressure, can be driven as an extreme case purely by magnetic interaction while also producing the observed spectrum and correlations.

Key words: accretion, accretion disks – galaxies: individual (PDS 456) – magnetohydrodynamics (MHD) – methods: numerical – quasars: absorption lines

1. Introduction

One of the generic features seen in black hole (BH) systems such as active galactic nuclei (AGNs) and Galactic X-ray binaries (XRBs) are blueshifted absorption features in their spectra primarily detected in the UV and the X-ray bands, with the latter also known as warm absorbers (WAs). Within the last decade, on the other hand, a new class of outflows has drawn much attention because of their unique physical characteristics: they are ejected at near-relativistic velocities \( (v/c \sim 0.1-0.7) \), with nearly Compton-thick columns \( (10^{23} \lesssim N_H \lesssim 10^{24} \text{ cm}^{-2}) \) and a systematically high ionization parameter\(^8\) \( (\log \xi \sim 4-6) \). These ultra-fast outflows (UFOs), primarily observed with high-throughput charge-coupled device (CCD) detectors, appear to be present not only in nearby Seyfert AGNs (e.g., Tombesi et al. 2010, 2011, 2014) but also in very bright (lensed) quasars (e.g., Chartas et al. 2003; Pounds et al. 2003; Chartas et al. 2009b; Dadina et al. 2018) and presumably in the ultraluminous X-ray sources (e.g., Walton et al. 2016). While WA/UFO signatures in the X-ray spectra are thought to be generic to accretion-powered sources, their launching mechanism is still poorly understood.

PDS 456 is an archetypical nearby \( (z = 0.184) \), radio-quiet quasar (QSO) hosting a BH of mass \( M \sim 10^9 M_{\odot} \) (e.g., Reeves et al. 2009), being the most luminous AGN in the local universe with a bolometric luminosity of \( L_{\text{bol}} \sim 10^{47} \text{ erg s}^{-1} \). It is among the best studied QSOs for its strong UFO signatures observed in the Fe K band in the past X-ray observations with\(^8\)

\[ \xi \equiv \frac{L_{\text{ion}}}{(nr^2)} \]

This is defined as \( \xi \equiv L_{\text{ion}}/(nr^2) \) where \( L_{\text{ion}} \) is the ionizing (X-ray) luminosity and \( n \) is the plasma number density at distance \( r \) from the BH.

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the wind density increases faster than the X-ray flux for $s < 2$, and therefore, increase in $L_{\text{ion}}$ will bring the wind ionization front to smaller radii, yielding higher plasma velocities.

While the wind kinematics is fully determined by the ideal MHD equations (e.g., BP82, Köngl & Kartje 1994, CL94, Kraemer et al. 2018), we consider a possibility of a truncated disk, as often discussed (e.g., Nemmen et al. 2014; Hogg & Reynolds 2018), by introducing an inner truncation launching radius, $R_T$. This parameter is constrained by fitting the observed UFO spectrum. Given the presence of the big blue bump (generally attributed to the accretion disk; see, Matzeu et al. 2016), we assume a fiducial value of $\theta_{\text{obs}} = 50^\circ$ for the inclination angle, as also previously suggested (e.g., Reeves et al. 2009, 2014; Hagoit et al. 2015). It should be noted that no radiation is deliberately taken into account in this work to illustrate the pure magnetic case.

Employing the self-similar prescription in the radial direction with the Keplerian velocity profile ($v \propto r^{-1/2}$), the poloidal field structure is determined by numerically solving the Grad-Shafranov equation as is originally formulated in CL94. Hence, the wind geometry is inherently 2.5-dimensional. The outflowing plasma is then photoionized by the radiation of spectral shape $F_\nu$, and luminosity $L_{\text{ion}}$ is assumed to be a compact region much smaller than the UV-emitting region (e.g., Churaya et al. 2009a; Morgan et al. 2012). We adopt the input spectral energy distribution (SED) of PDS 456 from M16 where simultaneous observations with XMM-Newton/OM and NuSTAR in 2014 are phenomenologically parameterized in a double broken power-law form, i.e., $\Gamma = 0.7$ for O/UV—10 eV, $\Gamma = 3.3$ for the soft X-ray band, and $\Gamma = 2.4$ beyond 0.5 keV (see also N15).

In response to the irradiating SED, the wind ionization is computed as described in F10, by employing xstar (Kallman & Bautista 2001) to calculate the local ionic abundances and the photo-ionization cross-section $\sigma_{\text{abs}}$. The latter is a function of the local wind velocity $v(r, \theta)$ and its radial shear $v_{\text{shear}}(r, \theta)$; the wind shear is implemented in the Voigt function $H(a, u)$ (see F10) to effect a physically motivated local line broadening consistent with the wind kinematics, instead of the arbitrary choice of a turbulent velocity (unphysical in its magnitude considering the much smaller thermal plasma velocities). A local line depth is calculated by $\gamma_\nu(r, \theta) = \sigma_{\text{abs}} N_{\text{ion}}$, where $N_{\text{ion}}$ is the local ionic column over a discretized small distance of $\Delta r$ ($\Delta r/r = 0.15$) along a line of sight (LoS). The observed spectrum is then a superposition of all local spectra over the entire wind (F10). The strength of the UFO feature is measured by EW as

$$\text{EW}(\theta) \equiv \int_{\text{wind}} \left[ 1 - \prod_{\text{wind}} e^{-\gamma_\nu(r, \theta)} \right] dv.$$  

### 3. Results

#### 3.1. UFOs in 2013/2014 Composite Spectrum

We first attempt to model a composite XMM-Newton/ NuSTAR spectrum in 2013/2014 where these observations were close together in time (4 days) and very little variability is noted. A detailed analysis and discussion are found in N15.

We analyze the spectrum of PDS 456 by assuming a canonical density slope of $p = 1.2$, as discussed above. Adopting the galactic absorption model with $N_H^{\text{Gal}} = 2.4 \times 10^{21} \text{cm}^{-2}$ (Kalberla et al. 2005), we initially...
excluded the Fe K band (~7 keV  E  11 keV in the rest-frame) to model the underlying continuum, following the earlier analysis by N15. As explained in Section 2, for a given X-ray luminosity of f_{44} = 5 (i.e., L_{ion}  5  10^{44} erg s^{-1}) in this specific epoch (Gofford et al. 2014; N15; M17), our primary model parameters include: (1) a wind truncation radius, R_{T}, and (2) the density normalization, n_{10}^b, as shown in Table 1 where we systematically explored the parameter space that yields the best-fit spectrum. To account for the presence of a broad P-Cygni profile at the Fe K band (see N15), a single Gaussian component at zga is (phenomenologically) added. With the above continuum, the absorption signature is fitted by our MHD wind model, mhdwind. This component significantly improves the fit with $\chi^2$/dof = 382.8/430 with $R_T/R_S = 7.98^{+0.7}_{-0.5}$ and $n_{10} = 9.1^{+2.8}_{-1.3}$ when $E_{P,Cyg}
$ is freely varied, while $\chi^2$/dof = 501.1/429 for $R_T/R_S = 7.90^{+0.3}_{-0.2}$ and $n_{10} = 7.6^{+0.46}_{-0.42}$ when fixed at $E_{P,Cyg} = 7.42$ keV as constrained in N15. The former best-fit yields $v/c \approx 0.35$ (the centroid velocity) and $v_{\text{max}}/c \approx 0.39$ (innermost wind velocity). Figure 1(a) shows the XMM-Newton/EPIC (black) and NuSTAR (red/green) composite spectrum of PDS 456 modeled with the MHD disk wind (blue) with free $E_{P,Cyg}$. Considering the implied high-velocity and ionization parameter, we only focus on the Fe XXVI ion in this work. The Ly/β line, while modeled here, is insignificant due to its lower oscillator strength as expected.

A radiative transfer calculation using xstar in thermal/ ionization equilibrium also provides us with a number of important wind quantities, i.e., the plasma temperature $T$, ionization parameter $\xi$, and the hydrogen-equivalent column density $N_{H}$ for the UFO, as listed in Table 2. It is seen that the Fe XXVI is formed in the innermost wind layer close to the truncated radius. The obtained best-fit solution ($n_{10}, R_T$) is well constrained as demonstrated in the confidence contour in Figure 1(b). We note that the best-fit result is almost independent of our choice of $p = 1.2$. Being encouraged by the successful modeling of the Fe UFO seen in the 2013/2014 data, we then investigate a variable nature of the reported UFO conditions in Section 3.2.

### 3.2. The UFO Correlations

Following the successful model fit to the 2013/2014 Fe K UFOs for PDS 456 in Section 3.1, we investigated the dependence of the UFO properties (i.e., $v$ and EW) on the ionizing X-ray luminosity depicted by $f_{44}$ while holding everything else constant for simplicity. It should noted that the radiation field plays no role in affecting outflow kinematics in this model. On the other hand, its ionization structure is greatly influenced. As studied in M17, we consider a variable luminosity of 1 $f_{44} < 26$ with $\theta = 50^\circ$ assuming that the wind geometry changes very little with changing $f_{44}$ if the

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**Table 1**

| Primary Parameter          | Value          |
|----------------------------|----------------|
| Truncation radius $R_T$ [in $R_S$] | 0, 2, 4, 8, 16, 32, 64, 128 |
| Wind density normalization $n_{10}$ | 0.01–40 |

**Notes.** We assume $M = 10^9 M_\odot$ (Reeves et al. 2009), $\theta_{obs} = 50^\circ$, and $p = 1.2$. $^b$ Wind density normalization in units of 10^{10} cm^{-3}.

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**Table 2**

| Variable          | Obtained Value |
|-------------------|----------------|
| $E_{P,Cyg}$ [keV] | 6.32^{+0.25}_{-0.23} (7.42; N15)$^b$ |
| Density normalization $n_{10}$ [10^{10} cm^{-3}] | 9.1^{+2.8}_{-1.8} (7.6^{+0.46}_{-0.42}) |
| LoS truncated radius $R_T/R_S$ | 7.98^{+0.5}_{-0.3} (7.90^{+0.3}_{-0.1}) |
| Fe XXVI UFO $v/c$ | 0.35 |
| log($v_{\text{max}}$/erg cm s^{-1})$^c$ | 5.5 |
| log($T_{\text{max}}$/K)$^d$ | 5.6 |
| $N_{H}$(Fe XXVI) [cm^{-2}] | 2.0 $\times$ 10^{23} |
| $\chi^2$/dof | 382.8/430 (501.1/429)$^b$ |

**Notes.** We assume $M = 10^9 M_\odot$ (Reeves et al. 2009), $\theta_{obs} = 50^\circ$, and $p = 1.2$. $^b$ A fixed value obtained from N15. $^c$ Wind density normalization in units of 10^{10} cm^{-3}. $^d$ Calculated value from the modeled centroid velocity. $^e$ Calculated value near the truncated radius at $r = R_T$.
underlying global magnetic field is sufficiently "stiff" against the change in radiation field (see also Everett 2005).

Figure 2(a) shows the expected correlations of the calculated Fe XXVI centroid velocity \( v_c / c \) (red) and its corresponding EW (black) as a function of \( f_{\text{xxvi}} \) for two cases: \( s = 0.9 \) (solid) and \( s = 3 \) (dashed) for comparison. For \( s = 0.9 \) where wind density increases faster than the X-ray flux with \( \dot{m}_a \), it is clearly seen that the velocity is well correlated with \( f_{\text{xxvi}} \) while its EW is anticorrelated with \( f_{\text{xxvi}} \) (i.e., X-ray Baldwin effect; Iwasawa & Taniguchi 1993) in a good agreement with data (e.g., M17, P17, Pa18, Pi18). In this case, the UFO location (i.e., ionization front) comes closer to the BH with increasing \( f_{\text{xxvi}} \) since its radial distance scales as \( r_{\text{Fe XXVI}} \propto \dot{m}_a^{-1/2} \). In contrast the, \( s = 3 \) case is ruled out in this model. We note, for \( s = 0.9 \), that the predicted Fe XXVI EW exhibits a peak as \( f_{\text{xxvi}} \) varies due to the fact that the wind becomes Thomson-thick. The exact peak position depends on the SED and the value of \( s \) as the wind flux increases with \( \dot{m}_a \). Hence, the increasing segment of the EW correlation is less likely to be observed in near-Eddington sources such as PDS 456 (shaded region in green, consistent with the data), but perhaps it is relevant in low/sub-Eddington Seyferts exhibiting conventional WAs and UFOs.

We show in Figure 2(b) the luminosity-dependence of the predicted Fe XXVI line profiles for \( 6 \leq f_{\text{xxvi}} \leq 26 \) with \( s = 0.9 \). The centroid energy gradually increases with \( f_{\text{xxvi}} \), while the line width generally decreases (thus reducing EW) qualitatively consistent with the multi-epoch Suzaku data (e.g., Matzeu et al. 2016). This can be explained in terms of photoionization of the present model; with increasing \( \dot{m}_a \), more plasma is channeled into the wind (i.e., \( n_\theta \propto \dot{m}_a \) as \( n_\eta \propto n_\theta \) from the disk and X-ray power increases as well (i.e., \( f_{\text{xxvi}} \propto \dot{m}_a \)). For \( n_\eta \propto \dot{m}_a \), the wind density increases faster than the X-ray flux and the wind ionization parameter \( \xi \) slowly decreases with \( \dot{m}_a \). This ionization change will inevitably prevent the wind from producing Fe XXVI as the source brightens. Therefore, only the gas at a smaller LOS radius (closer to the irradiating central X-ray source) where velocity is higher can be effectively photoionized to produce Fe XXVI. The dominant heating processes for such a large \( \dot{m} \) is Compton scattering and electron recoil. Hence, more X-rays are scattered within the near-Compton-thick wind, depleting the photoionizing flux in turn to suppress the efficiency of Fe XXVI production at larger \( \dot{m} \). With further increase in \( \dot{m}_a \), this effect becomes more prominent bringing the ionization front more inwards where the wind is faster, while reducing the EW more. These trends are consistent with the multi-epoch observations (M17, Pa18, Pi18). This will eventually lead to little production of Fe XXVI ions resulting in no spectroscopic detection (despite the presence of high-velocity winds at all times).

**4. Summary and Discussion**

We have employed the MHD accretion disk wind model introduced in our earlier works (F10, F17, F18) to account for the observed correlations of the Fe XXVI UFO in PDS 456. Our model does not include explicitly the effects of radiation pressure, as do models specifically built to consider radiatively driven outflows (e.g., Everett 2005; Higginbottom et al. 2014; Hagino et al. 2017; Nomura & Ohsuga 2017). These are expected to be significant in sources accreting close to their Eddington rate (\( \dot{m}_a \approx 1 \)) like PDS 456. We have demonstrated by spectral analysis that the observed Fe XXVI UFO feature of PDS 456 can be successfully reproduced within the framework the magnetically driven disk winds. Our MHD wind model can also account for the observed correlations of the UFO velocity and EW with X-ray flux over multi-epoch data. The model assumes that the wind mass flux can increase faster than X-rays, a situation not unreasonable in such high mass accretion objects where radiation can be trapped and advected with the flow. Figure 3 shows the calculated streamlines along with wind density \( n(r, \theta) \) and fiducial ionization parameter \( \xi(r, \theta) \) in the poloidal plane.

The near-Eddington luminosity of PDS 456 is crucial in producing an increase in the UFO velocity with \( f_{\text{xxvi}} \) since the Fe XXVI velocity is closely related to the local escape velocity. An increase in this velocity implies that the ionization front responsible for the UFO moves radially inwards. This seems natural only when flows are close to Thomson-thick (a fact determined not by the X-rays, but by the near-Eddington O/UV luminosity of PDS 456), which is conceivable as the O/UV photons are closely related to the mass accretion rate. Of support of this notion are the observations of a near-Eddington narrow-line Seyfert AGN, IRAS 13224-3809, which exhibits similar UFO correlations (Pinto et al. 2018). To explore this,
we have considered different density profiles and confirmed that the wind of \( p = 0.9 \) indeed produces a smaller Fe XXVI column (i.e., lower EW) than does the \( p = 1.5 \) case as discussed in Section 3.2.

Low/sub-Eddington AGNs, to the contrary, are not expected to have this effect, allowing the EW to increase with X-ray strength as depicted in Figure 2(a). Overall, we note that the exact slope of the calculated correlation is sensitive to the values of \( s \) and \( p \) as well as the X-ray SED, and the study of such dependences will be left as a future work.

Fast X-ray outflows have also been detected in BH XRBs (e.g., Miller et al. 2015, 2016) that can be considered as “scaled-down” AGN UFOs in this framework. With timescales much shorter than those in AGNs, fast XRB winds over many binary orbits with X-ray variability may provide us with another valuable clue to systematically understand those correlations as discussed here for PDS 456.

The planned future missions, such as XARM and Athena, will be able to better constrain the enigmatic UFO properties with unprecedented energy resolution, perhaps leading to an answer for the ultimate question of its launching mechanism.

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