Yet another UFO in the X-ray spectrum of a high-z lensed QSO

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\textbf{ABSTRACT}

\textbf{Aims.} Ultra-fast outflows (UFO) appear to be common in local active galactic nuclei (AGN) and may be powerful enough ($\dot{E}_{\mathrm{kin}}\approx10^{51}$ erg s$^{-1}$) to effectively quench the star formation in their host galaxies. To test feedback models based on AGN outflows, it is mandatory to investigate UFOs near the peak of AGN activity, that is, at high-z where only a few studies are available to date.

\textbf{Methods.} UFOs produce Fe resonant absorption lines measured above $\approx7$ keV. The most critical problem in detecting such features in distant objects is the difficulty in obtaining X-ray data with sufficient signal-to-noise. We therefore selected a distant QSO that is capable of installing a magnetic driving origin of the UFO.

\textbf{Results.} The X-ray spectrum of MG J0414+0534 is complex and shows signatures of cold absorption ($N_H\approx4\times10^{22}$ cm$^{-2}$) and of the presence of an iron emission line ($E_{\mathrm{kin}}\approx6.4$ keV, $E_{\mathrm{EW}}\approx95\pm53$ eV) consistent with it originating in the cold absorber. Our main result, however, is the robust detection (more than 5$\sigma$) of an absorption line at $E_{\mathrm{abs}}\approx9.2$ keV ($E_{\mathrm{hid}}\approx2.5$ keV observer frame). If interpreted as due to FeXXVI, it implies gas outflowing at $v_{\mathrm{out}}\approx0.3c$. To our knowledge, this is the first detection of an UFO in a radio-loud quasar at $z=1.5$. We estimated that the UFO mechanical output is $\dot{E}_{\mathrm{kin}}\approx2.5L_{\mathrm{bol}}$ with $p_{\mathrm{rad}}/p_{\mathrm{mech}}\approx17$ indicating that it is capable of installing significant feedback between the super-massive black hole (SMBH) and the bulge of the host galaxy. We argue that this also suggests a magnetic driving origin of the UFO.

\textbf{Key words.} galaxies: high-redshift – quasar: individual: MG J0414+0534 – X-rays: individual : MG J0414+0534

\section{1. Introduction}

Since the discovery of the relation between the mass of a supermassive black hole (SMBH) and the bulges of their host galaxies \citep[i.e., the “$M_\bullet-\sigma$ relation”,][]{Kormendy1995}, we know that SMBHs likely play a role in the formation and growth of the galaxies \citep{Fabian2012}. Active galactic nuclei (AGN)-driven ultra-fast outflows (UFOs) \citep{Tombesi2010} have been recently proposed as a major feedback process whereby sweeping out or compressing the interstellar gas may influence the formation and growth of the galaxies \citep{Fabian2012, King2015}.

Resonant absorption lines detected in the $\approx7$-10 keV energy range due to highly ionized iron are the UFO signatures. They are measured in both radio-quiet and radio-loud objects and both in type-I and -II AGNs \citep{Tombesi2010, Tombesi2010b, Gofford2013}. While the average properties of UFOs are known at low $z$, we have only a few UFO detections at $z\gtrsim1.5$, that is, where they may have acted to shape the $M_\bullet-\sigma$ relation seen today \citep{Hasinger2002, Chartas2002a, Chartas2003, Chartas2007, Lanzuisi2012, Vignali2015}.

Here we present the XMM-Newton spectrum of MG J0414+0534, a lensed (magnification factor $\mu\approx30$) \citep{Trotter2000, Minezaki2009} and radio-loud type-I QSO at $z=2.64$ \citep{Lawrence1995}. The target is also a hyper-luminous infrared and red QSO \citep{Lawrence1995, McLeod1998}. These objects are thought to represent a dust-enshrouded phase in AGN evolution during which nuclear winds are expected to be present and expel/heat the cold gas in the hosting galaxy \citep{Georgakakis2009, Urrutia2009} thus enabling feedback processes between the SMBH and the galaxy bulges \citep{Fabian2012, King2015}. In X-ray, the source was previously pointed by Chandra and the spectrum was described by an absorbed power-law ($F_\nu=1.7\pm0.1, N_H=4.7\pm0.7\times10^{22}$ cm$^{-2}$, errors at 90\% confidence level for one parameter of interest here and throughout the paper, Avni 1976) plus an iron line in emission ($E_{FeK\alpha}=6.4\pm0.1$ keV, $E_{FeK\beta}=200\pm100$ eV; Chartas et al. 2002).

\section{2. Data reduction and analysis}

XMM-Newton pointed to MG J0414+0534 on March 11, 2017. SAS-15 and the latest available software and response matrices were used to reduce and analyze the data. The observation lasted $\approx78$ and $\approx76$ ks for EPIC-pn and EPIC-MOS instruments, respectively. Since it was affected by soft-p$+$ flares, high-background intervals were removed through an iterative sigma-clipping procedure applied to the 10-15 keV band data; we were left with cleaned exposure times of 48.5, 66.5, and 69.1 ks of exposure for pn, MOS1, and MOS2, respectively.

The images of MG J0414+0534 are within $\approx3''$ \citep{Chartas2002} but they form a single “point-like” source in XMM-Newton.
The addition of a Gaussian in absorption at $E\approx 2.5$ keV ($E\approx 9.2$ keV rest frame) is required by the data ($\Delta \chi^2\approx 27$ for two parameters of interest corresponding, using the F-test, to a 5σ detection; model #2 in Table 1 and Fig. 3). Its EW is $\approx 235\pm 70$ eV (rest frame) and it is consistent to be narrow (if the line width is left free to vary we obtain $\Delta \chi^2 \approx 0.1$ and a 90% confidence upper limit of $\sigma \lesssim 250$ eV, rest frame). This makes an edge origin implausible for at least part of the feature as proposed for APM 08279+5255 (Hagino et al. 2017): indeed if we substitute the Gaussian with an edge we obtain a worst fit by $\Delta \chi^2 \approx 5$ for the same number of parameters. To test the absorption feature, we searched for its presence in each single EPIC detector dataset. We used the model #1 in Table 1 as a baseline. All the parameters of the model (except for the width of the lines which was fixed to $\sigma=0$) were free to vary. The result is plotted in Fig. 4. The absorption line is detected at more than 99% confidence level in both MOS1 ($\Delta \chi^2=14.2$ for two parameters of interest) and pn datasets ($\Delta \chi^2=13.0$ for two parameters of interest), while there are hints of its presence in the same energy range in the MOS2 ($\Delta \chi^2=3.5$ for two parameters of interest). A similar combination of independent detections is highly improbable. We performed 1000 Monte-Carlo simulations for each EPIC detector using model #1 of Table 1 as baseline. We searched for detections of spurious absorption lines between (rest frame) 7 and 14 keV (corresponding to outflow velocities of $-0.01$–0.6$c$) in the simulated spectra. We found that none of the 1000 simulations allowed us to obtain detections for which the line centroids are within 1 keV range for the three detectors (rest frame, see Fig. 4) and with a $\Delta \chi^2$ of at least 10 for two instruments and 3 for the other. Thus, considering the conservative approach that we used, we can assess that the probability of measuring an absorption feature as seen in MG J0414+0534 by chance is well below 0.1% and fully consistent with the combined probability obtained with the F-test (see above). Since the line is close to some instrumental edges ($E\approx 2.35$ and $E\approx 2.8$ keV), we also tried, without success, to account for the $E\approx 2.5$ keV feature allowing the detector gain to change (using “gain fit” within Xspec). We finally searched for a similar line in the longest Chandra exposure, finding that, fixing the line at $E=9.2$ keV, the EW is $\lesssim 130$ eV (90% confidence level); that is, if present, the line has varied since then ($EW\approx 235\pm 70$ eV today).

The detection of the FeKα emission line may indicate the presence of a reflection component. This feature is commonly observed in nearby Seyfert galaxies (e.g., Perola et al. 2002), and recently it has been detected also in some high-$z$ QSO (Dadina et al. 2016, Lanzuisi et al. 2016). To test this hypothesis and to further probe the robustness of the detection of the absorption feature against a more complex underlying continuum, we tried the Pexmon reflection model (Nandra et al. 2007) fixing the incli-
Table 1. Spectral models. **Upper table** Column 1: Model number; Column 2: absorbing column in excess to the Galactic value; Column 3: photon index; Column 4: energy of the emission line; Column 5: emission line rest frame EW; Column 6: energy of the absorption line; Column 7: absorption line EW; Column 8: 0.5-8 keV flux; Column 9: 2-10 keV flux; Column 10: $\chi^2$/d.o.f. **Lower table** Columns 1-5 as in upper table. Column 6: column density of the ionized absorber; Column 7: Log of the ionization parameter expressed in erg s$^{-1}$ cm; Column 8: observed redshift of the ionized absorber; Column 10: $\chi^2$/d.o.f. Line widths are fixed to 0 eV.

| # | $N_H$ (10$^{22}$ cm$^{-2}$) | $\Gamma$ | $E_{FeK\alpha}$ (keV) | EW$_{FeK\alpha}$ (keV) | $E_{abs}$ (keV) | EW abs (keV) | $F_{0.5-8}$ (10$^{-13}$ erg s$^{-1}$ cm$^{-2}$) | $F_{2-10}$ (10$^{-13}$ erg s$^{-1}$ cm$^{-2}$) | $\chi^2$/d.o.f. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.86$^{+0.47}_{-0.50}$ | 1.75$^{+0.05}_{-0.05}$ | 6.37$^{+0.10}_{-0.10}$ | 105$^{+54}_{-51}$ | 3.82 |
| 2 | 3.71$^{+0.60}_{-0.50}$ | 1.73$^{+0.05}_{-0.05}$ | 6.37$^{+0.11}_{-0.11}$ | 94$^{+53}_{-42}$ | 9.22$^{+0.31}_{-0.30}$ | 235$^{+74}_{-75}$ | 306.4/347 |

| # | $N_H$ (10$^{21}$ cm$^{-2}$) | $\Gamma$ | $E_{FeK\alpha}$ (keV) | EW$_{FeK\alpha}$ (keV) | $N_{H,ion}$ | Log($\xi$) | $z$ | $\chi^2$/d.o.f. |
|---|---|---|---|---|---|---|---|---|
| 3 | 3.67$^{+0.23}_{-0.22}$ | 1.69$^{+0.01}_{-0.07}$ | 6.37$^{+0.10}_{-0.11}$ | 79$^{+51}_{-54}$ | 83$^{+17}_{-50}$ | 3.89$^{+0.27}_{-0.54}$ | 1.72$^{+0.17}_{-0.17}$ | 297.9/344 |

Fig. 4. Confidence contours plot of the Gaussian absorption line normalization vs. its rest-frame energy for each single EPIC instrument. Contours confidence levels are as in Fig. 2.

Fig. 5. Unfolded X-ray observed frame energy spectrum of MG J0414+0534 (upper panel) obtained using model #3 in Table 1 and displayed in the middle panel. This model fits well the data and no strong residuals are left (lower panel). Color-code is as in Fig. 1.

3. Discussion and results

We present the results obtained analyzing the XMM-Newton data of the radio-loud quasar MG J0414+0534 taken on March 11, 2017. We probed its radio-loudness using the parameter $R=f_{GHz}/f_{4400}$A (R≥10 for radio-loud sources, Kellermann et al. 1989). To obtain the rest frame value of R we used the observed fluxes in H band ($m_H$≈13.95) (Skrutskie et al. 2006) and...
at 1.4 GHz ($f_{\text{1.4 GHz}}=2.1\pm0.1$ Jy, Condon et al. 1998). The result is that R = 780. The average shape of the X-ray continuum is very much in agreement with what was previously found by Chartas et al. (2002) for the brightest image (Image A) of the source. The photon index is $\Gamma \approx 1.7$ and there is a cold absorbing column of $N_H \approx 4\times10^{22}$ cm$^{-2}$. We also detected a cold iron line ($E_{\text{FeK}\alpha} = 6.4\pm0.1$ keV in emission with $EW_{\text{FeK}\alpha} = 95\pm53$ eV. According to the present analysis, the iron emission line may be due to the same matter responsible for the cold absorption assuming an almost spherical distribution of such a component (e.g., Leahy & Creighton 1993).

The observed luminosity of MG J0414+534, once corrected only for absorption, is $L_{\text{2-10keV}} = 1.5\times10^{46}$ erg s$^{-1}$ adopting a standard $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_\Lambda = 0.73$. If we assume the magnification factor $\mu = 45$ between the estimated values of 30 and 60 (Trotter, Winn, & Hewitt 2000; Minezaki et al. 2009), we can infer an intrinsic X-ray luminosity $L_{\text{2-10keV}} \approx 3\times10^{44}$ erg s$^{-1}$ that corresponds to an intrinsic $L_{\text{bol}} \approx 1\times10^{46}$ erg s$^{-1}$ assuming the bolometric correction factor ($k_{\text{bol}} \approx 30$) by Lusso et al. (2012). Based on the H$\beta$ broadening, the SMBH mass has been estimated to be $M_\bullet \approx 1.8\times10^9 M_\odot$ (Peng et al. 2006) and this implies that the source is emitting at $\approx 5\%$ of its Eddington limit ($L_{\text{Edd}} \approx 2\times10^{47}$ erg s$^{-1}$).

The main result of our analysis is the first detection, to our knowledge, of an UFO in a radio-loud object at $z \geq 1.5$. The absorption feature is due to iron resonant absorption (essentially FeXXVI) in ionized and outflowing gas (Log($\xi$) = -2.5 between the absorption line EW and the source flux observed in IRAS 13224–3809 (Parker et al. 2017) holds also at high-z, gravitational lensing helps in getting stronger features. However, the current absence of large enough samples of good-quality X-ray spectra of either lensed or non-lensed high-z QSO has hampered the study of these or other possible effects which must be accounted for if we want to understand how the feedback mechanism worked along cosmic time to shape the observed $M_\bullet - \sigma$ relation.

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References

Anni, Y. 1976, ApJ, 210, 642
Chartas, G., Agol, E., Eracleous, M., et al. 2002, ApJ, 568, 509
Chartas, G., Brandt, W. N., & Gallagher, S. C. 2003, ApJ, 595, 85
Chartas, G., Cappi, M., Hamann, F., et al. 2016, ApJ, 824, 53
Chartas, G., Eracleous, M., Dau, X., Agol, E., & Gallagher, S. 2007, ApJ, 661, 678
Chartas, G., Hamann, F., Eracleous, M., et al. 2014, ApJ, 783, 57
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
Crenshaw, D. M., Kraemer, S. B., & George, I. M. 2003, ARA&A, 41, 117
Dadina, M., Vignali, C., Cappi, M., et al. 2016, A&A, 592, A104
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Fabian, A. C. 2012, ARA&A, 50, 435
Georgakakis, A., Clements, D. L., Bendo, G., et al. 2009, MNRAS, 394, 533
Goobar, J., Reeves, J. N., Tombesi, F., et al. 2013, MNRAS, 430, 60
Hagino, K., Done, C., Okada, H., Watanabe, S., & Takahashi, T. 2017, MNRAS, 468, 1442
Hasinger, G., Schartel, N., & Komossa, S. 2002, ApJ, 573, L77
Hopkins, P. F., & Elvis, M. 2010, MNRAS, 401, 7
Kallman, T., & Bautista, M. 2001, ApJS, 133, 221
Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, AJ, 98, 1195
King, A., & Pounds, K. 2015, ARA&A, 53, 115
Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581
Lanzuisi, G., Giustini, M., Cappi, M., et al. 2012, A&A, 544, A2
Lanzuisi, G., Perna, M., Comastri, A., et al. 2016, A&A, 590, A77
Lawrence, C. R., Elston, R., Januzzi, B. T., & Turner, E. L. 1995, AJ, 110, 2570
Leahy, D. A., & Creighton, J. 1993, MNRAS, 263, 314
Lusso, E., Comastri, A., Simmons, B. D., et al. 2012, MNRAS, 425, 623
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
McLeod, B. A., Bernstein, G. M., Rieke, M. J., & Weedman, D. W. 1998, AJ, 115, 1377
Minezaki, T., Chiba, M., Kashikawa, N., Inoue, K. T., & Kataza, H. 2009, ApJ, 697, 610
Nandra, K., O’Neill, P. M., George, I. M., & Reeves, J. N. 2007, MNRAS, 382, 194
Parker, M. L., Pinto, C., Fabian, A. C., et al. 2017, Nature, 543, 83
Peng, C. Y., Impey, C. D., Rix, H.-W., et al. 2006, ApJ, 649, 616

Finally, it is worth noting here that MG J0414+534 is the seventh QSO at $z \geq 2.5$ in which UFOs have been detected. Excluding HS 1700+6416 (Lanzuisi et al. 2012) and PJD352 (Vignali et al. 2015) which are non-lensed, the remaining objects, namely APM 08279+5255, PG1115+080, H1413+117, HS 0810+2554 (Hasinger et al. 2002, Chartas et al. 2003, 2007, 2009, 2016) and MG J0414+534 are lensed. The flux enhancement due to the lensing does certainly help to collect good quality X-ray spectra and this may help in detecting such features. Alternatively, one can speculate that the flux enhancement makes it easier to probe weaker fluxes and, if the anti-correlation between the absorption line EW and the source flux observed in IRAS 13224–3809 (Parker et al. 2017) holds also at high-z, gravitational lensing helps in getting stronger features. However, the current absence of large enough samples of good-quality X-ray spectra of either lensed or non-lensed high-z QSO has hampered the study of these or other possible effects which must be accounted for if we want to understand how the feedback mechanism worked along cosmic time to shape the observed $M_\bullet - \sigma$ relation.
Perola, G. C., Matt, G., Cappi, M., et al. 2002, A&A, 389, 802
Pooley, D., Rappaport, S., Blackburne, J. A., Schechter, P. L., & Wambsganss, J. 2012, ApJ, 744, 111
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Tommasi, F., Cappi, M., Reeves, J. N., et al. 2010a, A&A, 521, A57
Tommasi, F., Cappi, M., Reeves, J. N., & Braito, V. 2012, MNRAS, 422, L1
Tommasi, F., Cappi, M., Reeves, J. N., et al. 2013, MNRAS, 430, 1102
Tommasi, F., Sambruna, R. M., Reeves, J. N., et al. 2010b, ApJ, 719, 700
Tommasi, F., Tazaki, F., Mushotzky, R. F., et al. 2014, MNRAS, 443, 2154
Trotter, C. S., Winn, J. N., & Hewitt, J. N. 2000, ApJ, 535, 671
Urrutia, T., Becker, R. H., White, R. L., et al. 2009, ApJ, 698, 1095
Vignali, C., Iwasawa, K., Comastri, A., et al. 2015, A&A, 583, A141