Winds of change: The nuclear and galaxy-scale outflows and the X-ray variability of 2MASS 0918+2117

P. Baldini\textsuperscript{1,2,3}, G. Lanzuisi\textsuperscript{3}, M. Brusa\textsuperscript{1,2}, A. Merloni\textsuperscript{3}, K. Gkimisi\textsuperscript{1}, M. Perma\textsuperscript{4}, I. E. López\textsuperscript{1,2}, E. Bertola\textsuperscript{5,1,2}, Z. Igo\textsuperscript{5,6}, S. Waddell\textsuperscript{1}, B. Masiuimenta\textsuperscript{1,2}, C. Aydar\textsuperscript{3,6}, R. Arcodia\textsuperscript{7,3,4}, G. A. Matzeu\textsuperscript{1,2,8}, A. Luminari\textsuperscript{9,10}, J. Buchner\textsuperscript{3}, C. Vignali\textsuperscript{1,2}, M. Dadina\textsuperscript{2}, A. Comastri\textsuperscript{2}, G. Cresci\textsuperscript{1}, S. Marchesi\textsuperscript{1,2,11}, R. Gilli\textsuperscript{2}, F. Tombesi\textsuperscript{12,13,14,9}, and R. Serafinelli\textsuperscript{10}

1 Dipartimento di Fisica e Astronomia “Augusto Righi”, Università di Bologna, Via Gobetti 93/2, 40129 Bologna, Italy
2 INAF – Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Gobetti 93/3, 40129 Bologna, Italy
3 Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße 1, 85748 Garching bei München, Germany
e-mail: baldini@mpe.mpg.de
4 Centro di Astrobiologia (CAB), CSIC-INTA, Ctra. de Ajalvir km 4, Torrejón de Ardoz 28850 Madrid, Spain
5 INAF – Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy
6 Exzellenzcluster ORIGINS, Boltzmannstr. 2, 85748 Garching, Germany
7 MIT Kavli Institute for Astrophysics and Space Research, 70 Vassar Street, Cambridge 02139, MA, USA
8 Quasar Science Resources SL for ESA, European Space Astronomy Centre (ESAC), Science Operations Department, 28692 Villanueva de la Cañada, Madrid, Spain
9 INAF – Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere 100, 00133 Roma, Italy
10 INAF – Osservatorio Astronomico di Roma, Via Frascati 33, 00078 Monte Porzio Catone Roma, Italy
11 Department of Physics and Astronomy, Clemson University, Kinard Lab of Physics, Clemson, SC 29634, USA
12 Department of Astronomy, University of Maryland, College Park 20742, MD, USA
13 Dipartimento di Fisica, Università degli Studi di Roma ‘Tor Vergata’, Via della Ricerca Scientifica 1, 00134 Roma, Italy
14 Istituto Nazionale di Fisica Nucleare, Sezione di Roma ‘Tor Vergata’, Via della Ricerca Scientifica 1, 00134 Roma, Italy

Received 22 December 2023 / Accepted 14 February 2024

ABSTRACT

Context. In this work, we test feedback propagation models on the test case of 2MASS 0918+2117 (2M0918), a $z = 0.149$ X-ray variable AGN that shows tentative evidence for nuclear ultra-fast outflows (UFOs) in a 2005 XMM-Newton observation. We also investigate whether UFOs can be related to the observed X-ray variability.

Aims. We observed 2M0918 with XMM-Newton and NuSTAR in 2020 to confirm the presence of and characterize the UFOs. We performed a kinematic analysis of the publicly available 2005 SDSS optical spectrum to reveal and measure the properties of galaxy-scale ionized outflows. Furthermore, we constructed 20-year-long light curves of observed flux, line-of-sight column density, and intrinsic accretion rate from the spectra of the first four SRG/eROSITA all-sky surveys and archival observations from Chandra and XMM-Newton.

Methods. We detect UFOs with $v \sim 0.16c$ and galaxy-scale ionized outflows with velocities of $\sim 700 \text{ km s}^{-1}$. We also find that the drastic X-ray variability (factors $>10$) can be explained in terms of variable obscuration and variable intrinsic luminosity.

Results. Comparing the energetics of the two outflow phases, 2M0918 is consistent with momentum-driven wind propagation. 2M0918 expands the sample of AGN with both UFOs and ionized gas winds from 5 to 6 and brings the sample of AGN hosting multiscale outflows to 19, contributing to a clearer picture of feedback physics. From the variations in accretion rate, column density, and ionization level of the obscuring medium, we propose a scenario that connects obscurers, an accretion enhancement, and the emergence of UFOs.

Key words. accretion, accretion disks – ISM: jets and outflows – galaxies: active – quasars: emission lines – quasars: general – quasars: supermassive black holes

1. Introduction

Most massive galaxies host at least one supermassive black hole (SMBH) in their inner regions. These SMBHs are known to be the engine of the powerful emitters known as active galactic nuclei (AGN), as they accrete gas in their vicinity. In the past 20 years, observational evidence of tight correlations between the properties of the host-galaxy and the SMBH (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Häring & Rix 2004), as well as theoretical arguments (e.g., Silk & Rees 1998) have led the astronomical community to believe that the assembly of the SMBH and the galaxy are connected (see Kormendy & Ho 2013 for a review).

In the AGN-galaxy coevolution framework, the enormous amount of energy that the AGN releases through accretion can severely impact the gas reservoirs of the host galaxy, possibly quenching or triggering star formation (e.g., Harrison 2017). This AGN “feedback” is now included in most cosmological simulations (e.g., Di Matteo et al. 2005; Sijacki et al. 2015; Pillepich et al. 2021) as it is a necessary ingredient to prevent the formation of galaxies of extreme stellar masses ($M_\ast > 10^{12-13} M_\odot$), which are indeed extremely rare in the universe.
A promising way AGN can enact feedback on the host is through disk winds or outflows that propagate throughout the galaxy (e.g., Fabian 2012). These winds have been observed on scales that range from subparsec to tens of kiloparsec (see, e.g., Cicone et al. 2018; Laha et al. 2021). They are usually revealed through emission or absorption lines that contain a blueshifted component due to the proper motion of the outflowing gas. These features have been observed on galaxy scales in the ionized (optical wavelengths), molecular (millimeter and submillimeter wavelengths) or neutral (radio) phases of the ISM, also with spatially resolved spectroscopy, which reveals complex interactions of the winds with the surrounding medium (e.g., Brusa et al. 2018; Finley et al. 2018; Saito et al. 2022; Cresci et al. 2023; Zanchettin et al. 2023). The galaxy-scale outflows have typical velocities of ~100–1000 km s⁻¹ (Fiore et al. 2017; Musiimenta et al. 2023).

Higher ionization levels are associated with winds closer to the central launching engine, the AGN. Broad absorption features in the soft X-rays and absorption lines above seven keV ascribed to blended blueshifted iron lines, respectively known as warm absorbers (WAs) and ultra-fast outflows (UFOs), trace such small-scale outflows. While WAs also have velocities of ~1000 km s⁻¹ and values of the ionization parameter ξ in the range log(ξ) ~ 0–2, UFOs are characterized by higher ionization states (log(ξ) > 4) and extreme relativistic velocities (up to 0.3c, Tombesi et al. 2010). UFOs are detected in >30% of local AGN (e.g., Tombesi et al. 2013; Igo et al. 2020; Matzeu et al. 2023), and are expected to generate multiphase galaxy-scale outflows by interacting with the ISM (King & Pounds 2015). However, whether the energy injected in the outflows is then efficiently radiated away or instead contributes to their adiabatic expansion is a question still left unanswered by theory. This is the origin of the momentum-driven versus energy-driven wind propagation mechanism dichotomy (e.g., Costa et al. 2014).

Observationally, simultaneously measuring outflow energetics on multiple scales for the same source can constrain the mechanism through which winds can propagate from the inner regions to the outskirts of the galaxy. Nevertheless, although the presence of multiphase large-scale outflows has been observed extensively (e.g., Herrera-Camus et al. 2019; Shimizu et al. 2019; Slater et al. 2019; Husemann et al. 2019; García-Bernete et al. 2021), there are only a handful of sources for which multiphase and multiscale outflows have been constrained (see the compilations of Tozzi et al. 2021; Bonanomi et al. 2023 and see Zanchettin et al. 2021). For almost all of the reported sources, by comparing the momentum outflow rates (P) of two different wind phases, the mechanism was consistent with one of the two proposed scenarios. However, the sample is still too small to derive trends with properties of the AGN. Moreover, the sample is dominated by sources in which the large-scale outflows are detected in the molecular phase, while only for five sources have the galaxy-scale outflows been detected in the optical ionized phase. An unbiased sample requires the characterization of large-scale feedback in all phases, and optical observations must catch up to the millimetric studies.

Winds are responsible for the large-scale impact of AGN on their host galaxies, and they have also been proposed as a possible explanation for the extremely variable changing-look AGN (CL-AGN; see Ricci & Trakhtenbrot 2023 for a review). Variability is a defining characteristic of AGN, which is observed on timescales that range from minutes to decades (Padovani et al. 2017). However, CL-AGN challenge our understanding of what happens at the center of active galaxies.

In the unified model (Urry & Padovani 1995), the AGN optical spectral classification of Type 1 versus Type 2 is ascribed to differences in the viewing angle. This is also true in the X-rays, where objects are classified either as obscured (line-of-sight column density N_H > 10²² cm⁻²) or unobserved (N_H < 10¹⁹ cm⁻²). This distinction is due to the presence of a dusty and molecular torus (Antonucci & Miller 1985; Ramos-Almeida & Ricci 2017), which can intercept and block out radiation coming from the very inner regions of the AGN and give rise to different spectral signatures. CL-AGN do not fit into this picture as they transition on timescales of months to years from one classification to another (e.g., Minutti et al. 2014; Yang et al. 2018).

For CL-AGN to exist, it is necessary for the static unified model to include dynamic processes that are not yet fully understood. These can take the form of accretion disk instabilities (e.g., Śniegowska et al. 2022), occultation events (Risaliti et al. 2007), or ignition-shutdown events (e.g., Matt et al. 2003; Gezari et al. 2017). In the last few years, an alternative mechanism in which the changing-look event is explained in terms of variable obscuration due to outflowing gas material has been proposed for some sources (e.g., NGC 5548, Kaastra et al. 2014; NGC 3227, Beuchert et al. 2015; and NGC 3783, Mehdipour et al. 2017). In addition, since the large-scale outflows are thought to be the result of variable nuclear phenomena, characterizing AGN variability can help us understand the full picture of AGN feedback.

In this work, we report a CL-AGN where UFOs significantly drive the X-ray variability. In addition to this, the AGN shows galaxy-scale outflows, which supports a momentum-driven scenario.

The paper is organized as follows. In Sect. 2 we present the source 2MASS 0918+2117, in Sect. 3 we describe how the data was reduced, and in Sect. 4 we describe the optical spectral analysis used to derive energetics for the ionized outflow. In Sect. 5 we describe the X-ray spectral analysis, and in Sect. 6 the X-ray variability. Lastly, in Sect. 7 we discuss the implications of our results. In this work we assume LCDM Cosmology, with H₀ = 69.6, Ω_M = 0.286, Ω_Λ = 0.714.

2. The case of 2MASS 0918+2117

Given the number of open questions and the limited size of the available samples, both regarding CL-AGN and AGN where multiphase outflows are detected, single-object studies can be highly insightful. Detailed multi-epoch spectral analysis can provide constraints on the mechanisms responsible for the observed spectral transitions. Moreover, careful spectral modeling is needed in order to reveal outflows in sources that do not constitute the exceptional bright end of the bulk of the AGN population.

2MASS 0918+2117 (2M0918) is a nearby (z = 0.149) Type 1.5 AGN discovered in the Two Micron All Sky Survey (2MASS, Cutri et al. 2002; Skrutskie et al. 2006). The most relevant parameters for 2M0918, including values derived from spectral energy distribution (SED) fitting with X-CIGALE (Yang et al. 2022, see Appendix A), are presented in Table 1.

2M0918 was the object of a total of eight X-ray observations (Table 2). The first three were discussed respectively in Wilkes et al. (2002, 2005), and Pounds & Wilkes (2007, hereafter PW07), and were taken respectively in 2001 with Chandra, and in 2003 and 2005 with XMM-Newton. We also followed up 2M0918 with XMM-Newton + NuSTAR in 2020 for a total of ~57 + 60 ks. Additionally, 2M0918 was also observed by eROSITA (Predehl et al. 2021, P21), aboard the...
Table 1. Summary of 2M0918 parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>09h 18m 48.61s</td>
</tr>
<tr>
<td>Dec</td>
<td>+21° 17'17.07''</td>
</tr>
<tr>
<td>z</td>
<td>0.149</td>
</tr>
<tr>
<td>(L_{\text{bol}})</td>
<td>(2.23 \times 10^{45} \text{ erg s}^{-1})</td>
</tr>
<tr>
<td>(M_\star)</td>
<td>(7.45 \times 10^{45} M_\odot)</td>
</tr>
<tr>
<td>SFR</td>
<td>0.12 (M_\odot) yr(^{-1})</td>
</tr>
<tr>
<td>(\log(M_{\text{BH}}/M_\odot))</td>
<td>7.4 ± 0.4</td>
</tr>
</tbody>
</table>

Notes. The bolometric luminosity \(L_{\text{bol}}\), the total stellar mass \(M_\star\), and star formation rate (SFR) were all estimated from the SED fitting procedure, described in Appendix A. The black hole mass \(M_{\text{BH}}\) was estimated from the optical analysis presented in Sect. 4.

3. Data reduction

The SDSS observed 2M0918 in November 2005. For our optical analysis, we downloaded the spectrum from the publicly accessible catalog\(^1\).

The X-ray observations, listed in Table 2, were reduced differently depending on the instrument. The 2003, 2005, and 2020 XMM-Newton observations have the longest exposure times of all the available X-ray observations. For all three observations, the pn (Strieder et al. 2001), and MOS1 and MOS2 (Turner et al. 2001) data were processed using the standard SAS v.20.0.0 procedures. We then extracted the spectra following the procedures of Piconcelli et al. (2004) and Bianchi et al. (2009), which maximize the signal-to-noise ratio (S/N) in a given band. We chose the hard 2–10 keV band as this is where UFO features should be found, and we only selected single and double pixel events (pattern 0–4 and 0–12 for pn and MOS, respectively). The S/N optimization works by testing combinations of multiple source extraction radii and background thresholds, given a fixed background extraction region. Using a background region of 50″, we found that the S/N is maximized in the 2–10 keV band for the pn, MOS1, and MOS2 extraction regions with radii of 33″, 32″, and 38″ respectively in 2003, 40″, 30″, and 40″ in 2005, and 17″, 20″, and 15″ in 2020. These correspond to encircled energy fractions (EEFs) of ~80–90% in 2003 and 2005 and ~60% in 2020. The response files were then generated with the SAS tasks RMFGEN and ARFGEN with the calibration EPIC files version v3.13.

The 2020 NuSTAR observations were taken three days after the XMM-Newton pointing. The data of the two cameras (FPMA and FPMB) were processed with the NuSTAR Data Analysis Software package (NuSTARDAS) version 2.1.2 within HEAsoft v6.30. We used the calibration files in the NuSTAR CALDB (version 20220510) and produced clean event files using the task NUPipeline with standard filtering criteria. We did not detect significant solar flares through the NUSTAR FILTER_LIGHTCURVE IDL script. We selected an extraction region with a radius of 40″ (~EEF), and simulated the background spectrum at source location using the NUSKYBGD IDL script (Wilk et al. 2014), which accounts for the position-dependent stray light component.

We binned the XMM-Newton spectra using the optimal binning option (Kaastra & Bleeker 2016) in the HEAsoft FTGROUPPHA task. For all three observations, the pn, MOS1, and MOS2 spectra were analyzed simultaneously, with the addition of the FPMA and FPMB spectra in the 2020 spectral set. We binned the NuSTAR spectra to one count per bin to preserve spectral resolution.

For the 2001 Chandra data, we used products extracted by the eROSITA Science Analysis Software System (eSASS; Brunner et al. 2022) pipeline in the latest version v4.8-6. For all four catalogs, the matching was positive and unambiguous. We subsequently downloaded the source products from the web toolbox DATool as extracted by the eROSITA Science Analysis Software System (eSASS; Brunner et al. 2022) pipeline in the latest available configuration (v. 211214). The products included light curves, ARFs, RMFs, and source and background spectra for each eRASS and for different telescope module (TM) combinations (see Liu et al. 2022 for details on how the source and background extraction regions are defined in the automated pipeline). We simultaneously analyzed the spectra of the combined TM1, TM2, TM3, TM4, and TM6, leaving out TM5 and TM7 because these modules are known to be affected by light leaks that contaminate observations (see P21). Due to the survey nature of the eROSITA observational strategy, exposure times are ~200 s, which correspond to photon counts <40 for 2M0918. For this reason, we do not bin the spectra and apply Bayesian methods suited for low-photon statistics, which are presented in Sect. 6.

\(^1\) https://dr12.sdss.org/
Table 2. Observation log of all the X-ray observations used to populate and analyze the X-ray light curve of 2M0918.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Obs. ID</th>
<th>Date</th>
<th>Exposure time (ks)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra</td>
<td>2159</td>
<td>2001-02-18</td>
<td>2</td>
<td>Wilkes et al. (2002)</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>0149170501</td>
<td>2003-04-24</td>
<td>8</td>
<td>Wilkes et al. (2005)</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>0303360101</td>
<td>2005-11-15</td>
<td>22</td>
<td>PW07</td>
</tr>
<tr>
<td>eROSITA (eRASS1)</td>
<td>–</td>
<td>2020-05-02</td>
<td>0.17</td>
<td>This work</td>
</tr>
<tr>
<td>XMM + NuSTAR</td>
<td>0870820101</td>
<td>2020-10-19</td>
<td>57+60</td>
<td>&quot;</td>
</tr>
<tr>
<td>eROSITA (eRASS2)</td>
<td>–</td>
<td>2020-11-03</td>
<td>0.14</td>
<td>&quot;</td>
</tr>
<tr>
<td>eROSITA (eRASS3)</td>
<td>–</td>
<td>2021-05-06</td>
<td>0.14</td>
<td>&quot;</td>
</tr>
<tr>
<td>eROSITA (eRASS4)</td>
<td>–</td>
<td>2021-11-05</td>
<td>0.14</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Notes. The last column reports the main references that analyzed a given observation previous to this work. The eROSITA exposure times are low due to its survey observation strategy.

---

4. Optical spectral analysis

We modeled the spectrum in two steps. First we fitted the continuum with a power law and the FeII empirical template presented in Véron-Cetty et al. (2004). The initial fit covered the entire wavelength range, but masked the prominent broad-line region (BLR) and narrow-line region (NLR) lines. We then proceeded to simultaneously fit the emission lines and the continuum using the template derived from the previous fit. Regarding the lines, we fitted eight narrow Gaussian lines (FWHM < 500 km s\(^{-1}\)) to account for the NLR emission of H\(\alpha\) and H\(\beta\), and the [OIII], [OIII], [NII], [NII], [SII], [SII] doublets were set to 1:299, assuming typical gas conditions (Osterbrock 1981). We also modeled the broad H\(\alpha\) and H\(\beta\) lines (FWHM > 2000 km s\(^{-1}\)) originating from the BLR with broken power laws convolved with Gaussian functions (e.g., Cresci et al. 2015; Perna et al. 2021). The broken power-law indices were tied between the two lines. Additionally, we included six moderately broad (500 km s\(^{-1}\) < FWHM < 2000 km s\(^{-1}\)) Gaussian components (H\(\alpha\), H\(\beta\), and the [OIII] and [SII] doublets) to account for turbulent kinematics or outflows. The widths, velocity shifts, and relative intensities were constrained as above. All fitted emission lines have a S/N of 8 or above.

Figure 1 shows the result of our fitting procedure in the H\(\alpha\) and H\(\beta\) regions. As shown by the orange curves in the plot, the outflowing component contributes significantly to the line emission and cannot be excluded by our model.

**Ionized gas kinematics and black hole mass**

The prescriptions we used to characterize the outflow kinematics have been established in the literature for over a decade (e.g., Cano-Díaz et al. 2012; Fiore et al. 2017). By assuming a spherical geometry of the outflow, the mass outflow rate can be computed as \(M_{\text{OF}} = 3 \times V_{\text{OUT}} \times M_{\text{OF}} \times R_{\text{OF}}^{-1}\), where \(V_{\text{OUT}}\) is the maximum outflow velocity, \(R_{\text{OF}}\) is the outflow radius, and \(M_{\text{OF}}\) is the mass of the gas entrained in the outflow.

Without spatially resolved spectroscopy, \(R_{\text{OF}}\) can only be constrained as an upper limit. Knowing that the fibers on the SDSS spectrograph are 3” in diameter, the observed outflow is contained within a 3.9 kpc radius at the redshift of this source. Following Cano-Díaz et al. (2012), the mass \(M_{\text{OF}}\) can be estimated from the integrated luminosity of the broad [OIII] line

\[
M_{\text{OF}} = 5.3 \times 10^{-5} \frac{L_{\text{44}}(\text{[OIII]})}{n_e 10^{0.4/4} M_\odot},
\]

where \(L_{\text{44}}(\text{[OIII]})\) is the luminosity of the outflow component of the [OIII] line in units of \(10^{44}\) erg s\(^{-1}\), \(10^{0.4/4}\) is the metallicity of the outflowing gas, and \(n_e\) is the electron density of the same gas in units of 1000 cm\(^{-3}\).

We estimated \(n_e = 0.16\) from the ratio \(R = 1.24\) of the two outflowing components of the [SII] doublet (assuming a
gas temperature of $10^4$ K, Osterbrock 1981), and we assumed solar metallicity. We measured the observed $L_{\text{H}α}([\text{OIII}]) = (7.9 \pm 0.2) \times 10^3$. However, this value is affected by host-galaxy extinction, which we quantified through the Balmer decrement method (Osterbrock & Ferland 2006). The observed Balmer ratio of the outflowing component is $H\alpha/H\beta = 3.9^{+0.2}_{-0.4}$. We adopted the Calzetti et al. (2000) extinction curve and, for an intrinsic $H\alpha/H\beta$ ratio of 2.86, we measured $E(B - V) = 0.30^{+0.14}_{-0.10}$ mag. The extinction-corrected [OIII] luminosity is therefore $L_{\text{H}α}([\text{OIII}]) = (2.1^{+0.3}_{-0.6}) \times 10^{-2}$.

For $V_{\text{OUT}}$ we used the common non-parametric maximum velocity estimator $v_{10}$, which corresponds to the 10th percentile of the overall line profile. We obtained $V_{\text{OUT}} \sim 700$ km s$^{-1}$ for [OIII]$_{5007}$. The derived mass outflow rate is then $M_{\text{OF}} = 3.7^{+0.5}_{-1.1} M_\odot$ yr$^{-1}$, and the momentum outflow rate $P$ and kinetic power $K$ are simply $P = M_{\text{OF}} \times V_{\text{OUT}} = (2.1^{+0.3}_{-0.6}) \times 10^{-1}$ $L_{\odot}$ c and $K = \frac{1}{2} \times P \times V_{\text{OUT}} = (5.6^{+0.8}_{-0.2}) \times 10^{11}$ erg s$^{-1}$.

We also performed a similar computation from the H$\beta$ line (see, e.g., Cresci et al. 2023). Using hydrogen lines has the advantage of releasing the assumption on the metallicity of the gas. However, the derived parameters are affected by the higher degree of degeneracy between the many emission components (i.e., the presence of BLR emission). With an observed broad H$\beta$ luminosity of $L_{\text{H}β}(H\beta) = (5.6^{+0.4}_{-0.3}) \times 10^{-3}$ we obtained $M_{\text{OF}} = 17.4^{+0.9}_{-1.0} M_\odot$ yr$^{-1}$, $P = (1.0 \pm 0.1) L_{\odot}$ c and $K = (2.6^{+0.3}_{-0.2}) \times 10^{10}$ erg s$^{-1}$. The energetics derived from H$\beta$ are larger by a factor of 4.7 than the values obtained from [OIII], in line with the results by Fiore et al. (2017).

We measured the mass of the SMBH through the single-epoch virial method, which is based on the empirical $R_{\text{BLR}} \propto L^{0.5}$ relation discovered through reverberation mapping studies (e.g., Kaspi et al. 2005). We used the relation presented in Dalla Bonta et al. (2020) (Eq. (38)), which makes use of the broad H$\beta$. The Balmer ratio in the BLR is $H\alpha/H\beta = 8.58^{+0.65}_{-0.45}$, so the intrinsic luminosity is $L_{\text{H}α}(H\beta) = (1.7^{+2.0}_{-0.3}) \times 10^{-1}$With a line dispersion of $σ \sim 1100$ km s$^{-1}$, this corresponds to a mass of $log(M_{\text{BH}}/M_\odot) = 7.4 \pm 0.4$, where the errors are conservatively estimated to be 0.4 dex, based on the argument presented in Shen (2013).

5. X-ray spectral analysis I: Searching for winds

We reanalyzed the 2005 XMM-Newton spectrum (shown in Fig. 2), first presented in PW07, in order to confirm the UFO model. We did so through the XSPEC spectral fitting package v.12.12.0 (Arnaud 1996) by first identifying the best continuum model, and subsequently looking for excess emission or absorption features in the hard band.

We first fitted the three EPIC spectra simultaneously with a simple Galactic absorption and power-law model (XSPEC: CONST × TBABS × POWER2) within 0.5 and 10 keV, in order to model the continuum. We used a Galactic absorption of $N_{\text{H}} = 4 \times 10^{20}$ cm$^{-2}$, as derived from the HEASOFT task NH (Kalberla et al. 2005). This initial model is insufficient and cannot reproduce the whole spectrum, with a C-stat value of 817 over 273 degrees of freedom (d.o.f.). The residuals (Fig. 2, middle panel), show a deficit of counts below 1 keV and an excess in the 1–2 keV band, suggesting the presence of an absorber in the data.

When fitting multiple spectra, the addition of a constant is needed in order to account for different instrumental normalization.

We included in our model a photoionized and partially covering absorber to the model (ZGAUSS) to account for the deviations in the soft band. The residuals are less scattered (Fig. 2, bottom panel), and the fit considerably improves (C-stat: 329 over 270 d.o.f.). The fit parameters are shown in Table 3. The value of the absorber’s $N_{\text{H}}$ is very mild, while the ionization parameter is consistent with a neutral obscuring medium. This is used as our base continuum model in the following analysis.

We then looked for hard absorption and emission features, through a line scan, as first proposed in Cappi et al. (2009). The procedure, which has been extensively used in the literature (e.g., Tombesi et al. 2010; Bertola et al. 2020; Matzeu et al. 2023) operates as follows. The baseline continuum model is fit and its C-stat value is stored. A narrow, unresolved line (XSPEC: ZGAUSS, with $σ = 10$ keV) is added to the model, free to vary in both positive and negative normalization, to account for both emission and absorption features. The line energy is shifted 100 times between 5 and 10 keV (rest frame), and, for each of these energies, normalization is allowed to vary both positively and negatively 100 times as well in a range visually selected. The C-stat value of each of these 100 × 100 combinations is stored. Contour plots are then produced for values of $ΔC$ of $+2.3$, $-4.61$, $-5.99$, and $-9.21$, which correspond to 68%, 90%, 95%, and 99% confidence level fit improvement.

Guided by the results shown in Fig. 3, we then fitted a narrow emission line between 6 and 7 keV. The fit significantly improved (99%), and the line was found at $E = 6.5^{+0.3}_{-0.1}$ keV, with an equivalent width of $0.10 \pm 0.04$ keV. The inclusion of this line in the model improves the C-stat to 319 over 268 d.o.f., which corresponds to an $F$-test significance of 98%. As this line is compatible with the known iron Kα transition ($E = 6.4$ keV), we include it in our baseline model.

The two hard absorption features are less significant. Fitting one narrow Gaussian component, we find a line at $E = 9.1 \pm 0.1$ keV, with a fit improvement of $ΔC$/d.o.f. = 7/2, which corresponds to an $F$-test significance of 95%. If we move the initial value of the line energy towards the second ~8 keV feature, the new local minimum is at $E = 8.0 \pm 0.2$ keV. The improvement is even less significant ($ΔC$/d.o.f. = 5/2 → $F$-test: 87%).
Table 3. Values for best-fit continuum models for the 2005 and 2020 XMM-Newton and NuSTAR observations.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>ZXIPCF</td>
<td>$N_H$</td>
<td>$(5.2 \pm 0.1) \times 10^{21}$</td>
<td>cm$^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>log($\xi$)</td>
<td>$&lt;-0.19$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Covering fraction</td>
<td>$0.84 \pm 0.03$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>POWERLAW</td>
<td>Photon index</td>
<td>$2.07 \pm 0.07$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalization</td>
<td>$(5.8 \pm 0.6) \times 10^{-4}$</td>
<td>photon keV$^{-1}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>2020</td>
<td>ZXIPCF</td>
<td>$N_H$</td>
<td>$5.0_{-0.7}^{+0.6} \times 10^{22}$</td>
<td>cm$^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>log($\xi$)</td>
<td>$1.1_{-0.4}^{+0.2}$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Covering fraction</td>
<td>$0.81_{-0.07}^{+0.05}$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>POWERLAW</td>
<td>Photon index</td>
<td>$2.11_{-0.15}^{+0.18}$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalization</td>
<td>$(1.7 \pm 0.5) \times 10^{-4}$</td>
<td>photon keV$^{-1}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
</tbody>
</table>

Notes. Significant variations are present in the column density, ionization parameter, and power-law normalization (intrinsic luminosity). All errors are at 1σ level.

The contours for both of these lines are shown in Fig. 4 where it is evident that the 99% curve does not close, as is consistent with null normalization.

We performed a similar analysis on the 2020 XMM-Newton and NuSTAR spectra, which are shown in Fig. 5. Following the same approach as in the 2005 case, but extending the energy range up to 20 keV, we find once again that the source is best reproduced by a CONST*TABSB*ZXIPCF*POWERLAW model. The simple power-law model has a value of C-stat/d.o.f. of 560/521, which improves to 490/518 with the inclusion of the absorber.

Although the model is the same, some parameters show significant changes from the 2005 to the 2020 observations: the absorber, which was previously consistent with not being ionized, has increased its ionization parameter $\xi$ by more than one order of magnitude, and the column density also increased by a factor of ~10. The intrinsic luminosity measured in the 2–10 keV band through the CLUMIN task also decreased significantly: log($L_{2-10, 2020}$) = 43.37 ± 0.01 versus log($L_{2-10, 2005}$) = 43.91 ± 0.01. The covering fraction and photon index remained consistent between the two observations.

We repeated the same line scan procedure previously performed on the 2005 spectra, and obtained the contours shown in Fig. 6, top panel for the 2020 spectra. The iron $\kappa$ line at 6.4 keV is no longer present, although a less significant emission line at 7.1 keV is evident. At around 8 keV, the contours reveal the presence of a broad absorption feature which appears to be due to the blending of two different lines. However, when the two features are modeled independently, neither is very significant ($\Delta C$/d.o.f. = 6/2) and revealing their separation is challenging. A more robust fit is obtained when the feature is modeled as one single broad Gaussian. By allowing $\sigma$ to vary, we find a line at $E = 8.2_{-0.3}^{+0.6}$ keV and $\sigma = 0.47_{-0.2}^{+0.8}$ keV, with a statistic
improvement of $\Delta C$/d.o.f. $= 11/3 \rightarrow F$-test: 99.2% (Fig. 6, bottom panel).

5.1. Wind significance assessment

As shown in Protassov et al. (2002), the F-test should not be taken at face value when estimating the significance of emission and/or absorption lines, as it can lead to overestimations. In order to robustly quantify whether the features are physical or are due to random fluctuations of the spectra, we made use of Monte Carlo simulations as follows.

We used the continuum models in Table 3, with parameters set to those found in our analysis, to simulate $3 \times 5000$ spectrum and background pairs for the 2005 observations (pn, MOS1, and MOS2), and $5 \times 5000$ pairs for the 2020 data (pn, MOS1, MOS2, FPMA, and FPMB). We also included the 6.5 keV emission line in the 2005 continuum. After binning the simulated data with the same criteria as in the analysis, we fitted the two sets of spectra with the same models used to produce them. We stored the C-stat value and the number of d.o.f. of each fit. We then re-fitted the spectra with an added Gaussian line, free to vary between 4 and 10 keV (source rest frame) and to be in either absorption or emission. The line was stepped through all of its allowed energy range in order to find the absolute fit minimum. We did so as our interest is in how often random fluctuations are mistaken for spectral lines in general, and not just limited to our specific energy and normalization. We stored once again the C-stat value and d.o.f. We then counted the instances where the inclusion of the Gaussian component produced an improvement in the fit ($\Delta C_{\text{sim}}$), with respect to the continuum model, greater than the improvement we observed in the real data ($\Delta C_{\text{real}}$). This translates into the probability that our observed feature is actually just a count fluctuation. The significance of the line detection is therefore

$$P = 1 - \frac{N_{\Delta C_{\text{real}} > \Delta C_{\text{real}}}}{N_{\text{tot}}},$$

Notes. Outflow velocity $V_{\text{OUT}}$ was obtained from the $z$ parameter.

For the 2005 and 2020 observations we first tested the inclusion of a narrow line. We also tested a broad line for the 2020 observations, with $\sigma$ set to 0.47 keV, and constrained between 0.2 and 0.8 keV, motivated by previous results. From our simulations, none of the narrow detections (two in 2005 and two in 2020) are significant ($<1\sigma$). Instead, the broad 2020 8.2 keV feature is significant at 98%. We note that this is larger than the threshold of significant detection commonly used in population studies (95%, Tombesi et al. 2010; Matzeu et al. 2023).

This result motivated us to further analyze the 2020 data. Instead of one broad Gaussian, we fitted ad hoc XSTAR tables (Kallman 1999). These models can be used to compute the physical conditions of the outflow, which are parameterized by the column density ($N_{\text{H}}$), the ionization parameter ($\xi$), and the turbulent velocity ($v_{\text{turb}}$). The model also includes a redshift parameter $z$, which can be converted into an outflow velocity.$^3$

We tested two tables, one with a turbulent velocity of 1000 km s$^{-1}$ and one with 5000 km s$^{-1}$: after stepping the redshift parameter between $-0.4$ and 0.1, as was first done in Tombesi et al. (2011), we find a minimum at $z = -0.017 \pm 0.008$, with a fit improvement of $\Delta C$/d.o.f. $= 18/3$ (Fig. 7). The values of the XSTAR parameters are reported in Table 4, and are fully consistent with typical Seyfert 1 UFOs.

We note that the fit improves much more significantly when the UFO is modeled as photoionized gas (XSTAR), rather than as a Gaussian absorption line. This is because the photoionized gas model accounts for a variety of absorption lines on a broad spectral range ($\sim$1–10 keV). As the outflow does not only contain iron, this model better reproduces the data compared to a Gaussian absorption line, which only models the most prominent iron absorption feature (see, e.g., Pounds & Page 2006).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Parameter & Value & Units \\
\hline
$\log(\xi)$ & $3.69 \pm 0.08$ & – \\
$N_{\text{H}}$ & $(2.3 \pm 0.9) \times 10^{23}$ & cm$^{-2}$ \\
$V_{\text{OUT}}$ & $0.16 \pm 0.02$ & c \\
\hline
\end{tabular}
\caption{XSTAR table parameter values.}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{example_graph.png}
\caption{\textbf{Fig. 6.} Results of line search for 2020 observations. Top: line scan contours of the 2020 observations. Bottom: contour plots of the absorption feature of the 2020 XMM-Newton spectra modeled as a broad line. The figures are to be interpreted as in Figs. 3 and 4, respectively.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{example_graph.png}
\caption{\textbf{Fig. 7.} $\Delta C$ value of the fit, as a function of the parameter $z$ in UFO velocity space. The dash-dotted and dashed horizontal lines correspond respectively to 68% and 90% confidence regions.}
\end{figure}
The intrinsic UFO column density is larger than the observed beaming \( \beta \) in Luminari et al. (2020), the relativistic velocities of UFOs \( \beta \). The UFO mass outflow rate can be derived as the same recipe as in Nardini & Zubovas (2018):

\[
\dot{M} = \frac{4 \pi}{3} c^3 n \Omega \sin \theta \left( \frac{1}{2} \right) \rho \rho_0^{1/3}
\]

Values for best-fit continuum models for the six observations analyzed to build the light curve.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra – 2001</td>
<td>ZTBABS</td>
<td>( \dot{N}_\text{H} )</td>
<td>&lt;3.6 \times 10^{21}</td>
<td>cm(^{-2})</td>
</tr>
<tr>
<td></td>
<td>POWERLAW</td>
<td>Photon index</td>
<td>1.8 \pm 0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalization</td>
<td>1.75^{+9.9}_{-6.5} \times 10^{-4}</td>
<td>photon keV(^{-1}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>XMM – 2003</td>
<td>TBPCF</td>
<td>( \dot{N}_\text{H} )</td>
<td>6.4^{+4.2}_{-3.0} \times 10^{22}</td>
<td>cm(^{-2})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Covering fraction</td>
<td>0.76^{+0.1}_{-0.17}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POWERLAW</td>
<td>Photon index</td>
<td>2.03 \pm 0.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalization</td>
<td>(1.4 \pm 0.2) \times 10^{-4}</td>
<td>photon keV(^{-1}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>eRASS1</td>
<td>TBPCF</td>
<td>( \dot{N}_\text{H} )</td>
<td>–</td>
<td>cm(^{-2})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Covering fraction</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POWERLAW</td>
<td>Photon index</td>
<td>1.94 \pm 0.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalization</td>
<td>1.6^{+2.8}_{-1.8} \times 10^{-4}</td>
<td>photon keV(^{-1}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>eRASS2</td>
<td>TBPCF</td>
<td>( \dot{N}_\text{H} )</td>
<td>–</td>
<td>cm(^{-2})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Covering fraction</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POWERLAW</td>
<td>Photon index</td>
<td>1.94^{+0.23}_{-0.25}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalization</td>
<td>&lt;1 \times 10^{-4}</td>
<td>photon keV(^{-1}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>eRASS3</td>
<td>TBPCF</td>
<td>( \dot{N}_\text{H} )</td>
<td>–</td>
<td>cm(^{-2})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Covering fraction</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POWERLAW</td>
<td>Photon index</td>
<td>2.06^{+0.23}_{-0.25}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalization</td>
<td>2.4^{+4.3}_{-1.7} \times 10^{-4}</td>
<td>photon keV(^{-1}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>eRASS4</td>
<td>TBPCF</td>
<td>( \dot{N}_\text{H} )</td>
<td>3.1^{+14.6}_{-3.0} \times 10^{21}</td>
<td>cm(^{-2})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Covering fraction</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POWERLAW</td>
<td>Photon index</td>
<td>2.03^{+0.24}_{-0.24}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normalization</td>
<td>3.4^{+3.3}_{-1.3} \times 10^{-4}</td>
<td>photon keV(^{-1}) cm(^{-2}) s(^{-1})</td>
</tr>
</tbody>
</table>

5.2. UFO energetics

The UFO mass outflow rate can be derived as \( \dot{M} = \Omega N_H m_p V_{\text{out}} R \), where \( m_p \) is the proton mass, and \( \Omega \) is the solid angle subtended by the outflow. We adopt the same recipe as in Nardini & Zubovas (2018): \( \Omega/4\pi = 0.5 \) and \( R = 2c/V_{\text{out}}/c \), which is the escape radius in units of gravitational radii \( r_s = GM_{\text{BH}}/c^2 \). This assumes that the UFO has reached a terminal velocity equivalent to this escape velocity at a distance \( R \) from the SMBH. Additionally, as discussed in Luminari et al. (2020), the relativistic velocities of UFOs can cause the underestimation of the outflow column densities by a factor 20–120% for \( V_{\text{out}} = 0.1c – 0.4c \). As a result of beaming effects, this can significantly offset the value of \( \dot{M} \). The intrinsic UFO column density is larger than the observed XSTAR \( N_H \) by a factor \( \Psi = (1 + \beta)/(1 - \beta) = 1.38 \pm 0.06 \), where \( \beta = V_{\text{out}}/c \). This corresponds to a mass outflow rate \( \dot{M} = (7.5 \pm 4.2) \times 10^{-3} M_\odot \text{yr}^{-1} \), a momentum outflow rate \( P = (3.1 \pm 1.7) \times 10^{-3} L_{\text{bol}}/c \), and kinetic power of \( K = (5.5 \pm 3.1) \times 10^{43} \text{ erg s}^{-1} \). These values are reported in Table 5, together with the energetics of the galaxy-scale ionized outflow derived from [OIII] and H\(_\alpha\).

6. X-ray spectral analysis II: Populating the light curve

In this section we derive the 20-year X-ray light curve in the 0.5–2 keV band, using the observations listed in Table 2. The energy range was chosen both for its sensitivity to variations in \( N_H \), and because it guarantees good performance for all of the instruments considered in this analysis. The 2005 and 2020 spectra have already been presented and analyzed. In the following subsections we analyze each observation in chronological order. The results of our fit procedure are shown in Table 6.


The Chandra spectrum has a total of 155 counts in the 0.5–7 keV range. Prompted by the previously obtained results, we modeled
The 2003 spectra are comprised of 467, 208, and 153 counts for pn, MOS1, and MOS2 respectively. We initially modeled the three spectra simultaneously in the 0.5–10 keV range with the same simple absorbed power-law model, as was done in the XMM-Newton observation. However, the fit was of poor quality (C-stat: 287/198 d.o.f.), and while the absorber is not needed in the fit, the inferred photon index is $\Gamma = 1.17 \pm 0.12$, which is well below the average AGN photon index of 1.8 (Nandra & Pounds 1994; Dadina 2008; Ricci et al. 2017). A photon index of less than 1.4 at 90% confidence has been used in literature as a selection criterion for highly obscured AGN (Lanzuisi et al. 2013, 2018; Georgantopoulos et al. 2013), as an absorbed power law with an intrinsically steeper photon index can be mimicked by an unabsorbed power law with a flatter photon index (George & Fabian 1991). We therefore insisted on including an absorber in the model.

The previously used XZIPCF model has too many parameters, for which degeneracies are not solvable with such photon statistics. Given the evidence for the absorber being cold in the 2005 data, we opted for the cold partial covering absorber model TBPCF. With a C-stat value of 280/196 d.o.f., we find a covering fraction of 0.76$^{+0.21}_{-0.12}$, and a photon index $\Gamma = 2.03 \pm 0.14$, both in agreement with the results obtained in Sect. 5. The partially covering absorber has a column density of $N_H = 6.4^{+2.5}_{-2.2} \times 10^{22}$ cm$^{-2}$.

We note that in the hard band some spectral features, such as iron lines, are still present in the residuals in Fig. 10, but as the focus of our spectral analysis is soft flux estimation we are satisfied with our best-fit model.

### 6.3. eROSITA – 2020–2021

Given the low exposure times (see Table 2), and the low photon counts (respectively 17, 5, 17, and 39 photons for eRASS1-4), we analyzed the eROSITA spectra within the Bayesian framework. We used the software Bayesian X-ray Analysis (BXA4, Buchner et al. 2014), which connects the nested sampling algorithm UltraNest5 package (Buchner 2021) with the fitting environment CIAO/Sherpa (Freeman et al. 2001; Fruscione et al. 2006).

We chose to use this analysis technique as it is particularly well suited for low photon statistics as no binning or assumption of Gaussianity of the parameter distribution is needed. Moreover, BXA also includes the possibility to simultaneously model the background with empirical principal component analysis (PCA) models (see Simmonds et al. 2018 for details on background PCA models).

We modeled the four unbinned spectra and backgrounds (shown in Fig. 11) simultaneously in the 0.2–10 keV range. SHERPA includes XSPEC models, and therefore for consistency
with all of the XMM-Newton(+NuSTAR) observations, we modeled the source as a power law absorbed by TBPCF with covering fraction fixed at 80%, with the usual Galactic absorption. BXA, which is of Bayesian nature, allows us to include priors on the parameters, which we set to be uniform on the log of the power-law normalization and the column density of the absorber. This means that we assume total ignorance of these parameters prior to our analysis. We instead implement a Gaussian prior for the photon index with $\Gamma = 1.95$ and $\sigma = 0.15$, based on the thoroughly observed distribution discussed in Sect. 6.2. Given our low photon counts, and the softness of the eROSITA response, it is crucial to have some constraints on the photon index.

Figure 12 shows the resulting corner plot, produced with the Python module Corner.py (Foreman-Mackey 2016), where contours represent credibility regions, rather than confidence levels. The fit is insensitive to the local absorber in all eRASSes except no. 4 (the brightest), in which we find moderate absorption $(\log(N_{\text{H}}) = 21.49^{+0.74}_{-1.74})$. We also note that the source is consistent with being undetected in eRASS2.

### 6.4. The 20-year light curve

We show the 20-year observed flux X-ray light curve in Fig. 13 (top), which includes fluxes from all the presented spectra. Variability is evident and recurrent, with the 2005 XMM-Newton observation being 11 times brighter than the 2003 observation and 6 times brighter than the 2020 observation. The dimmest state is the one associated with eRASS2, where the source was consistent with being undetected. However, this was only 14 days after a clear XMM-Newton detection, and if we take the upper error bar to be the 3$\sigma$ upper limit on the eRASS2 flux, the two values are compatible with small variability. However, the flux did increase again by a factor of 5.3 with respect to the 2020 XMM-Newton observation in eRASS4.

The middle panel of Fig. 13 shows the value of $N_{\text{H}}$ throughout the epochs, in clear anticorrelation with the observed flux (we exclude eRASS 1–3 as the fit was insensitive to variations in column density for these observations). In other words, dimmer states correspond to higher inferred column density, while brighter states correspond to lower quantities of obscuring material. This would favor a scenario in which the recurring alternating between high and low flux states is driven by a change in the absorbing material, which is not uncommon (see, e.g., Torricelli-Ciamponi et al. 2014 and references therein for other examples of variable $N_{\text{H}}$ in AGN).

We also plot the intrinsic flux variation over time in the bottom panel of the same figure. This shows that the intrinsic flux increases significantly between 2003 and 2005 and then drops again in 2020. The flux ratios are 11.6 (2005/2003) and 7 (2005/2020). We note that the eRASS2 upper limit is not consistent with the 2020 XMM-Newton intrinsic flux measurement. The data seem to indicate a drop of a factor of $\sim 2$ in only 14 days.

### 7. Discussion

In this section, we first present a discussion on the multiphase and multiscale winds and, subsequently, a discussion on the
interpretation of the observed variability. We finalize with a discussion on future perspectives of this work.

7.1. Multiphase and multiscale outflows

One of the most relevant features of our analysis is the simultaneous detection of multiphase winds. As mentioned in the introduction, AGN feedback is thought to propagate from small, subparsec scales all the way to galaxy and group or cluster scales. Although this is commonly accepted both from a theoretical and computational point of view (King & Pounds 2015; Costa et al. 2020), the physics of feedback is still not fully clear. More specifically, it is not yet known whether winds propagate in a momentum-driven fashion, where radiation cooling is faster than the outflow and so energy is not conserved, or in an energy-driven scenario, where cooling is negligible and the wind shock-front expands adiabatically. While theory deems both mechanisms to be suitable, observations can constrain this by measuring disk-scale (UFOs) and galaxy-scale winds (molecular, atomic, or ionized phase) in the same galaxy. A collection of sources for which energetics in at least two phases are available was compiled by Marasco et al. (2020), and later extended by Tozzi et al. (2021) and Bonanomi et al. (2023). However, the sample is still small (17 sources + Mrk 509, reported in Zanchetti et al. 2021), especially for sources with simultaneous detections of UFOs and galaxy-scale outflows in the ionized gas phase. With 2M0918 we are able to expand the number of sources in which both a UFO and an ionized outflow are detected from 5 to 6.

In Fig. 14 we add 2M0918 and Mrk 509 to the diagnostic plot presented in Marasco et al. (2020), Tozzi et al. (2021), and Bonanomi et al. (2023). The vertical axis shows the ratio of the momentum outflow rates, respectively of the galaxy- and disk-scale winds. Observations consistent with a momentum-driven scenario would lie on the horizontal dashed line, while the pink squares represent the energy-driven predictions. As shown in the gray-shaded area, 2M0918 is consistent with a momentum-driven scenario. Our results corroborate the conclusion drawn by Marasco et al. (2020) and Tozzi et al. (2021), that the energy- and momentum-driven models of feedback propagation explain the observation well, at least up to galaxy scales. We note that for some of the sources, the points fall below the momentum-driven prediction. This can be likely explained by the fact that ionized winds are ejected hundreds to thousands of years before the observations, and therefore the X-rays might be tracing a more energetic later event.

In Fig. 15 we plot the outflow momentum rate of 2M0918 normalized by $L_{bol}/c$ as a function of outflow velocity (green stars), together with the other five sources with detected UFOs and ionized outflows (pink). This is another standard diagnostic for feedback mechanisms, as winds conserving momentum in their propagation would lie on the dashed line parallel to the $x$-axis, while energy-driven winds would follow the descending line. Once again, despite the energetics derived from the [OIII] and H$_\alpha$ lines differing by almost one order of magnitude, 2M0918 generally occupies a region of the plane consistent with a momentum-driven scenario.

It is important to mention that the radius inferred for the optical ionized outflow is technically an upper limit, as we are using the diameter of the SDSS optical fiber. However, typical outflow radii for the ionized phase are ~1 kpc (see, e.g., Fiore et al. 2017); therefore, we do not expect to be underestimating the momentum outflow rate by a factor larger than 4, which would not change the feedback propagation scenario. In addition, recent results (e.g., Baron & Netzer 2019; Davies et al. 2020), which made use of the trans-auroral ratio (TR) method first introduced in Holt et al. (2011) to determine $n_e$ in outflows, suggest that the [SII] doublet method might systemically underestimate the true electron densities by even one order of magnitude. With our data, we cannot test this method as it requires the observation of lines that would fall at infrared wavelengths. As an increase in the density of the gas would push the $P_{out}$ down by an equal factor, the interplay between this uncertainty and the uncertainty on the radius makes us confidently state that our observations are consistent with a momentum-driven scenario.

7.2. Tracks in the $N_H$–$L_{EDD}$ plane and bolometric luminosities

Active galactic nuclei caught in active feedback phases are expected to be located in a specific region of the $N_H$–$L_{EDD}$ plane (Fabian et al. 2008). This is due to the interplay between the intensity of radiation pressure from accretion and the gravitational force that acts on the dusty obscuring material. In other words, as the accretion rate increases, only very heavy nuclear absorbing clouds can survive the intense radiation field. In Fig. 16 we plot the $N_H$–$L_{EDD}$ plane, as adapted from Ricci et al. (2022), with the density contours found from the Swift-BAT AGN Spectroscopic Survey sample (BASS) presented in the same paper. The positions spanned by 2M0918 are included in the plot.

While the column density $N_H$ was derived from the spectral analysis described previously, the Eddington ratio is defined as $\lambda_{EDD} = L_{bol}/L_{EDD}$, with the Eddington luminosity $L_{EDD} = 1.26 \times 10^{38}(M/M_\odot)$ being a constant only dependent on the mass of the black hole (for a mass of log($M/M_\odot$) = 7.4 ± 0.4 this is $L_{EDD} = (3.2^{+8.8}_{-1.9}) \times 10^{45}$ erg s$^{-1}$). Even though SED fitting is generally
considered one of the best probes for the bolometric luminosity, it is not a tracer of variability. By assuming that changes in the intrinsic X-ray emission are due to variations in accretion rate, deriving the bolometric luminosity from the 2–10 keV band is more suited to account for variability.

For our purposes, therefore, we estimate the AGN bolometric luminosity using the bolometric correction ($k_{\text{bol}} \equiv L_{\text{bol}}/L_{2-10}$). We use the bolometric corrections presented in Duras et al. (2020):

$$k_{\text{bol}}(L_{2-10}) = 15.33 \times \left[ 1 + \left( \frac{\log(L_{2-10}/L_\odot)}{11.48} \right)^{16.2} \right].$$

By applying this equation to the XMM-Newton, XMM-Newton (NuSTAR), and eROSITA-eRASS4 2–10 keV fluxes we obtain the $\lambda_{\text{EDD}}$ in Table 7. From these results and referring to Fig. 16, it is evident that 2M0918 has been living for the past 20 years in the vicinity of the “forbidden” outflow region of the $N_{\text{H}}-\lambda_{\text{EDD}}$ plane, possibly crossing it throughout its evolution. Moreover, the 2020 observation, in which UFOs were detected, falls inside the outflow region, although errors are large due to the uncertainty on the SMBH mass. Changes in accretion rate are also present, which provides us with further hints on the nature of the variability of 2M0918, which we describe and interpret in the next section. Overall, these results are consistent with our conclusions and demonstrate the potential of using the $N_{\text{H}}-\lambda_{\text{EDD}}$ plane for short-time variability rather than secular evolution.

We emphasize that the underlying assumption in this treatment is that winds are radiation-driven. It should be noted that other mechanisms, which we do not explore in this work, can also be responsible for the launching of winds. These include but are not limited to magnetically driven winds (e.g., Lynden-Bell 1996; Yuan et al. 2015; Fukumura et al. 2022) and thermally driven winds (e.g., Begelman et al. 1983; Waters & Proga 2018).

7.3. The nature of the variability of 2M0918

In Sect. 6 we derived the 20-year X-ray light curve from cross-instrument spectral analysis. The choice of individually modeling each spectrum, instead of simply fitting all observations with the same power-law model and looking for changes in normalization, enables (with some degree of uncertainty) the variability of the different components to be disentangled.

The spectral variability observed in 2M0918 is sufficiently drastic in order to classify this as a CL-AGN. Ricci & Trakhtenbrot (2023) divide CL-AGN into two classes based on whether the variability is to be ascribed to changes in the line-of-sight obscuring material (changing-obscuration AGN, CO-AGN; Mereghetti et al. 2021) or to changes in accretion state (changing-state AGN, CS-AGN, Graham et al. 2023).
X-ray CL-AGN are typically associated with CO-AGN, and some degree of obscuration variability is observable in a large fraction of the general AGN population (e.g., Risaliti et al. 2002; Markowitz et al. 2014). This is usually attributed to eclipsing events from gas clouds in the BLR (which is the case for the famous NGC 1365, Risaliti et al. 2009; Maiolino et al. 2010) or the clumpy nature of the dusty torus (see Ramos-Almeida & Ricci 2017 for a review). There is no particular reason why we should not consider these as valid scenarios for the observed variability of 2M0918: timescales range from days to years and the variations in $N_H$ are well within the observed range. However, these models do not predict or require any variation in the AGN accretion rate, which we observe (Fig. 16). We would then have to explain the accretion changes as uncorrelated to the obscuration and the result of disk instabilities (Sniegowska et al. 2022). We emphasize once again that these models should be kept in mind as possible explanations of the observed light curve; however, it is also possible to explore the plausibility of a connection between the two phenomena.

In the last decade, an alternative mechanism in which the CO-AGN event is explained in terms of obscuration due to outflowing gas material has been proposed for some sources (such as NGC 5548, Kaastra et al. 2014; NGC 3227, Beuchert et al. 2015; and NGC 378, Mehdipour et al. 2017). Additionally, Marchesi et al. (2022) explained the X-ray spectral variability of NGC 1358 within a recurring feeding-feedback framework. In

![Fig. 14](updated figure from Bonanomi et al. (2023), first presented in Marasco et al. (2020) and Tozzi et al. (2021), with the addition of 2M0918 (gray shaded area) and Mrk 509 (Zanchettin et al. 2021). This plot contains a compilation of sources for which UFO and galaxy-scale wind energetics are available, with the large-scale winds being either ionized, molecular or atomic. The ratio of the outflow momentum rates $P_{\text{OUT}}/P_{\text{UFO}}$ is plotted for each source, together with values predicted from theory for momentum-driven or energy-driven scenarios. The predicted value can be estimated as the ratio $V_{\text{OUT}}/V_{\text{UFO}}$ by imposing the conservation of energy, while the dashed line at $P_{\text{OUT}}/P_{\text{UFO}} = 1$ is the prediction of a momentum-driven scenario. For 2M0198, the average between the $P_{\text{OUT}}$ derived from [OIII] and $H_\alpha$ was used. The compilation uses various reported values (Bischetti et al. 2019; Braito et al. 2018; Chartas et al. 2009; Ciccone et al. 2014; Feruglio et al. 2015, 2017; García-Burillo et al. 2014; González-Alfonso et al. 2017; Longinotti et al. 2015, 2018; Lutz et al. 2020; Marasco et al. 2020; Mizumoto et al. 2019; Reeves & Braito 2019; Rupke et al. 2017; Sirressi et al. 2019; Smith et al. 2019; Tombesi et al. 2015; Tozzi et al. 2021; Veilleux et al. 2017; Zanchettin et al. 2021).

![Fig. 15](Updated momentum outflow rate normalized by $L_{\text{bol}}/c$ vs. outflow velocity for 2M0918 (green stars, different components as labeled). The two solid lines correspond to the two different feedback mechanisms described in the text, as labeled. In the background are also plotted the sources from Marasco et al. (2020) and Tozzi et al. (2021) where galaxy scale winds are ionized, each with its respective diagnostic line.)

![Table 7](Eddington ratio for each observation.)

<table>
<thead>
<tr>
<th>Observation</th>
<th>$\lambda_{\text{edd}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra – 2001</td>
<td>0.13$^{+0.01}_{-0.08}$</td>
</tr>
<tr>
<td>XMM-Newton – 2003</td>
<td>0.05$^{+0.08}_{-0.03}$</td>
</tr>
<tr>
<td>XMM-Newton – 2005</td>
<td>0.44$^{+0.67}_{-0.26}$</td>
</tr>
<tr>
<td>XMM+NuSTAR – 2020</td>
<td>0.11$^{+0.17}_{-0.07}$</td>
</tr>
<tr>
<td>eRASS – 2021</td>
<td>0.25$^{+0.38}_{-0.15}$</td>
</tr>
</tbody>
</table>

**Notes.** The large uncertainties on the mass strongly affect these values.

Table 7

<table>
<thead>
<tr>
<th>Observation</th>
<th>$\lambda_{\text{edd}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra – 2001</td>
<td>0.13$^{+0.01}_{-0.08}$</td>
</tr>
<tr>
<td>XMM-Newton – 2003</td>
<td>0.05$^{+0.08}_{-0.03}$</td>
</tr>
<tr>
<td>XMM-Newton – 2005</td>
<td>0.44$^{+0.67}_{-0.26}$</td>
</tr>
<tr>
<td>XMM+NuSTAR – 2020</td>
<td>0.11$^{+0.17}_{-0.07}$</td>
</tr>
<tr>
<td>eRASS – 2021</td>
<td>0.25$^{+0.38}_{-0.15}$</td>
</tr>
</tbody>
</table>

**Notes.** The large uncertainties on the mass strongly affect these values.
These cases the absorber is ionized to some degree, but for low S/N observations, its imprint on the spectra can mimic that of neutral gas (see, e.g., Waddell et al. 2024).

For 2M0918 the ionization parameter $\xi$ was observed to increase by an order of magnitude between 2005 and 2020 (the two observation sets in which the S/N was high enough to disentangle the degeneracy in the ZXIPC parameters), concurrent with an increase in column density. These are the same observations in which UFO signatures were detected. At the same time, between 2003 and 2020 (Fig. 16), the AGN entered, crossed, and left the $N_{H}/^{\text{H - EDD}}$ plane region in which sources are expected to be in the outflowing phase. We propose, based on these considerations, that the observed variability can be associated with outflowing gas.

We propose the following scenario, which explains the variability in accretion rate, absorber column density, and the appearance of winds in one unified scheme:

- In 2001 the source was observed in a mild-Eddington state. Some amount of clumpy obscuring gas was present in the nuclear regions, as is currently accepted in AGN models, but was not significantly obscuring the source.
- In 2003 the source was obscured, due to gas intercepting the line of sight. This transition could either be explained in terms of a simple Keplerian orbit of an uneven clumpy medium, but also as an inflowing motion of the gas. The 2005 observations favor the second option (see next bullet point).
- In 2005 we observed the AGN in a brighter state than before, accreting close to the Eddington limit. This may have been due to the AGN accreting part of the gas that caused the increase in obscuration in 2003, with a resulting increase in intrinsic luminosity and a decrease in column density.
- In 2020 the source appeared to be obscured once again, but this time the absorbing material was ionized to a mild degree. The AGN dimmed back to its original state. We attribute the absorption to outflowing clouds intercepting the line of sight, pushed and ionized by the UFO, and ionized by the high radiation field generated from the previous accretion event.

- At the end of 2021 the source went back to its original mild-Eddington unobscured state, as the UFOs successfully cleared the surrounding gas. The AGN is now slightly brighter than it was in 2001, but not significantly.

Figure 17 shows a cartoon of the proposed scenario. Although we strongly support this model, based on our analysis, it must be noted that the timescales on which the accretion rate changes propagate through standard Shakura–Sunyaev accretion disks are the viscous timescales,

$$\tau_{\text{vis}} \sim 400 \left( \frac{H/R}{0.05} \right)^{-2} \left( \frac{\alpha}{0.03} \right)^{-1} \left( \frac{R}{150 r_{\odot}} \right)^{3/2} M_{\odot} \text{yrs}, \tag{4}$$

where $H/R$ measures the thickness of the disk, $\alpha$ is the viscous coefficient, $R$ is the radius at which the timescale is computed in units of gravitational radii, and $M_{\odot}$ is the SMBH mass in units of $10^{8} M_{\odot}$. Assuming standard prescriptions, the viscous timescales for 2M0918 are on the order of tens of years. This is a factor of $\sim 10$ times longer than the observed variability of two years, which would make our observations incompatible with theoretical predictions. However, it must be noted that the standard $\alpha$-disk has been recognized by theorists as an oversimplification for quite some time, and some solutions, such as a thick(er) disk or the role of magnetic fields, have been proposed to release assumptions, which would also shrink the timescales for accretion rate changes (see Lawrence 2018 for a discussion; see also Komossa & Grupe 2023 and references therein).

We also note that the episodic accretion event does not necessarily have to be communicated to the whole disk in order for luminosity to increase. In the case of tidal disruption events (TDEs), which are events in which black holes accrete stars passing in their vicinity, super-Eddington accretion disks can form on timescales of days (see, e.g., Gezari 2021 for a review). Although gas accretion and TDEs are different phenomena, we believe that variations in $H/R_{\text{edd}}$ can in principle happen on timescales shorter than those predicted by Eq. (4), even for gas streams. For example, this could be the case if the accretion stream was coplanar with the accretion disk (e.g., Chan et al. 2019).

7.4. Future perspectives

We believe monitoring the source with simultaneous X-ray and optical observations will help further constrain the nature of the variability of 2M0918. The future X-ray mission Einstein Probe (Yuan et al. 2022) dedicated to the monitoring of transients will provide further constraints on the variability of 2M0918. Furthermore, optical IFU observations will allow us to directly infer the geometry of the outflows, tightening our constraints on the ionized outflow energetics. This approach has been extensively used both at low-z (e.g., Venturi et al. 2021, 2023; Speranza et al. 2022, 2024) and at high-z (e.g., XID2028, Cresci et al. 2015, 2023). The use of (sub)millimeter facilities, such as the Atacama Large Millimeter Array (ALMA), will allow us to probe the molecular phase of the outflow, which to date remains totally unprobed and is thought to contain most of the gas involved in the outflow.
Acknowledgements. The authors thank the anonymous referee for their constructive comments. The authors thank Claudio Ricci, Giulia Tozzi, and Francesca Bonanomi for their contribution to data visualization and Nicola Locatelli for the useful discussion. This work is based on data from eROSITA, the soft X-ray instrument aboard SRG, a joint Russian-German science mission supported by the Russian Space Agency (Roskosmos), in the interests of the Russian Academy of Sciences represented by its Space Research Institute (IKI), and the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The SRG spacecraft was built by Lavochkin Association (NPOI) and its subcontractors, and is operated by NPOI with support from the Max-Planck Institute for Extraterrestrial Physics (MPE). The development and construction of the eROSITA X-ray instrument was led by MPE, with contributions from the Dr. Karl Remeis Observatory, Bamberg & ECAP (F.cn Erlangen-Nuernberg), the University of Hamburg Observatory, the Leibniz Institute for Astrophysics Potsdam (AIP), and the Institute for Astronomy and Astrophysics of the University of Tübingen, with the support of DLR and the Max Planck Society. The Argelander Institute for Astronomy of the University of Bonn and the Ludwig Maximilians Universität Munich also participated in the science preparation for eROSITA. The eROSITA data shown here were processed using the eSASS/NRTA software system developed by the German eROSITA consortium. Funding for the Sloan Digital Sky Survey (SDSS) has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Cerro Tololo Inter-American Observatory, College of Charleston, University of Columbia, University of Connecticut, University of Delaware, The Faber Institute, University of Florida, University of Heidelberg, Henry Krannert Planetarium, University of Minnesota, University of New Mexico, University of Notre Dame, University of Pennsylvania, University of Toronto, University of Utah, University of Virginia, University of Washington, and University of Wisconsin.

References

Buchner, J. 2015, J. Open Source Softw., 6, 3001
Fabian, A. C. 2012, ARA&A, 50, 455
Foreman-Mackey, D. 2016, J. Open Source Softw., 1, 24
Appendix A: SED fitting with X-CIGALE

In our analysis of 2MASS 0918+2117, we meticulously estimated crucial physical parameters through spectral energy distribution (SED) fitting. The photometric data, obtained from the NED database, spanned diverse wavelength bands, including 2-10 keV, 0.5-2 keV, far-UV, and near-UV (GALEX), ugriz from SDSS, JHKs from 2MASS, W1-4 from WISE, and 24 and 160 microns from MIPS. We incorporated intrinsic flux data derived from the 2005 XMM-Newton observation. Utilizing a Chabrier (Chabrier 2003) initial stellar mass function (IMF) with solar metallicity and adopting a delayed star formation history for the stellar population, we employed Cigale models (Boquien et al. 2019; Yang et al. 2022) for the SED fitting. Dust extinction was accounted for using the model by Dale et al. (2014). AGN contributions were delineated using Skirtor, allowing various inclinations, polar obscuration, and an extensive AGN fraction grid. The resulting best fit, depicted in Fig. A.1, exhibited a reduced chi-square of 0.94.

The Bayesian posterior analysis yielded key parameters, notably an accretion luminosity \( L_{\text{acc}} = 2.32 \pm 0.17 \times 10^{45} \text{erg/s} \), a total bolometric luminosity \( L_{\text{bol}} = 2.95 \pm 0.15 \times 10^{45} \text{erg/s} \), and a host galaxy mass \( M_\star = 6.62 \pm 1.18 \times 10^{10} \text{M}_\odot \). These findings offer valuable insights into the properties of 2MASS 0918+2117, particularly concerning the bolometric luminosity, which was directly calculated from the SED, which enhanced the precision and reliability of our results, rather than relying on proxies.

Fig. A.1. SED of 2M0918 as modeled with CIGALE, with residuals. As shown by the labels, the model includes templates for stellar, nebular, dust, and AGN emission, as well as dust attenuation.