Near-infrared Variability of Obscured and Unobscured X-Ray-selected AGNs in the COSMOS Field

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Abstract

We present our statistical study of near-infrared (NIR) variability of X-ray-selected active galactic nuclei (AGNs) in the COSMOS field, using UltraVISTA data. This is the largest sample of AGN light curves in YJHK, bands, making it possible to have a global description of the nature of AGNs for a large range of redshifts and for different levels of obscuration. To characterize the variability properties of the sources, we computed the structure function. Our results show that there is an anticorrelation between the structure function A parameter (variability amplitude) and the wavelength of emission and a weak anticorrelation between A and the bolometric luminosity. We find that broad-line (BL) AGNs have a considerably larger fraction of variable sources than narrow-line (NL) AGNs and that they have different distributions of the A parameter. We find evidence that suggests that most of the low-luminosity variable NL sources correspond to BL AGNs, where the host galaxy could be damping the variability signal. For high-luminosity variable NL sources, we propose that they can be examples of “true type II” AGNs or BL AGNs with limited spectral coverage, which results in missing the BL emission. We also find that the fraction of variable sources classified as unobscured in the X-ray is smaller than the fraction of variable sources unobscured in the optical range. We present evidence that this is related to the differences in the origin of the obscuration in the optical and X-ray regimes.

Key words: galaxies: active – infrared: galaxies – methods: statistical – surveys – X-rays: galaxies

1. Introduction

Active galactic nuclei (AGNs) are one of the most energetic phenomena in the universe and are characterized by their time-variable continuum flux in every waveband in which they have been studied. Variability studies are fundamental to understanding the extreme physical conditions of accretion disks near supermassive black holes. The characteristic timescale of the variability ranges from days to years, and the variability magnitude is stronger in the X-ray, UV, and optical ranges.

AGNs are commonly classified in the optical range by the presence or absence of broad permitted emission lines (FWHM ≥ 2000 km s⁻¹), into broad-line (BL) AGNs (or type I) and narrow-line (NL) AGNs (or type II), respectively. The unified model is one of the most successful approaches to explain this dichotomy. It postulates that a dusty torus around the central engine is responsible for the different classes of AGNs, which occur when we observe the source at different angles (Antonucci & Miller 1985). The most promising models include a clumpy torus and disk winds (see Netzer 2015 and references therein), as they would explain the torus spectral energy distribution (SED) observed in the near-infrared (NIR) and mid-infrared (MIR) bands and the existence of at least some “changing look” AGNs (Tolomei & Osterbrock 1976; Denney et al. 2014; Shappee et al. 2014; LaMassa et al. 2015; Ricci et al. 2016). Other objects might require more drastic modifications to the unified model, like those that seem to lack a broad-line region (BLR), called by some authors “true type II” AGNs (Panessa & Bassani 2002; Elitzur & Netzer 2016) or weak emission line quasars (WLQs; Diamond-Stanic et al. 2009; Shemmer et al. 2009; Wu et al. 2012; Luo et al. 2015; Shemmer & Lieber 2015). Moreover, the relation between the optical and X-ray obscuration is still a debatable matter (Merloni et al. 2014; Burtscher et al. 2016; Marchesi et al. 2016b). Variability analysis can improve our understanding of these issues, as observations at different wavelengths trace different structures.

There is significant evidence of a strong correlation between the X-ray, UV, and optical variability (Uttley et al. 2003; Arévalo et al. 2008, 2009; Breedt et al. 2009, 2010; McHardy et al. 2016; Taley et al. 2016; Buisson et al. 2017), where the emission at shortest wavelengths is driving the variations. Also, correlations between the NIR and optical bands have recently been established (Suganuma et al. 2006; Lira et al. 2011, 2015). The rest-frame optical emission comes primarily from the accretion disk, and the infrared emission comes mostly from the dusty torus (Lira et al. 2011, 2015), whereas the SED of an AGN around the rest-frame wavelength of λ ~ 1 μm samples simultaneously two emission components, the accretion disk and the hottest part of the dusty torus. This has been confirmed both photometrically and spectroscopically (Glass 1992; Landt et al. 2011). Besides, Lira et al. (2015) found evidence of the presence of NIR emission from the accretion disk in the J- and H-band observations of MCG-6-30-15 by cross-correlating optical and NIR light curves.
AGN variability seems to be well described as a stochastic process (Kelly et al. 2009, 2014; Graham et al. 2014; Simm et al. 2016). Power spectral density (PSD) analysis is a useful tool to analyze the physical processes involved in the stochastic variability of AGNs. The PSD measures the variability power per temporal frequency $\nu$. However, the irregular sampling of ground-based light curves complicates the PSD analysis. Previous analysis shows that AGN power spectra are well described by a broken power law with a PSD $\propto 1/\nu^2$ after the break (Collier & Peterson 2001; Czerny et al. 2003; Kelly et al. 2009), which is consistent with damped random walk (DRW) or autoregressive processes. Kelly et al. (2014) showed that AGN light curves can also be well described by continuous-time autoregressive moving average (CARMA) models, which fully account for irregular sampling and measurement errors. From these models, the power spectra of AGNs can have different shapes, depending on the CARMA parameters used to model the light curve. Simm et al. (2016) showed that most of their sources (around 90 type I AGNs) were best described by a CARMA(2,0) process (i.e., the PSD can be represented by a broken power law, which, after the break, has a slope different than $-2$), which means that most of their sources deviate from a simple DRW model.

To understand the physics behind AGNs we need multiwavelength variability studies, from which we can determine the contribution of the distinct components of the emission. But multiwavelength projects are expensive and difficult to accomplish. Several authors have studied the optical, UV, and X-ray variability of AGNs for a significant number of sources (e.g., Cristiani et al. 1996; Nandra et al. 1997; Giveon et al. 1999; Turner et al. 1999; Vanden Berk et al. 2004; de Vries et al. 2005; Rengstorf et al. 2006; Schmidt et al. 2010; MacLeod et al. 2011; Palanque-Delabrouille et al. 2011; Graham et al. 2014; Lanzuisi et al. 2014; Cartier et al. 2015; Simm et al. 2016; Caplar et al. 2017). However, very little is known about the variability in the NIR range. The study of AGN variability in the NIR is particularly difficult, since the contamination from the host galaxy in this wavelength region can be large (Hernán-Caballero et al. 2016). Therefore, for most sources, the NIR variability of the central source is overshadowed by the emission from the galaxy. Neugebauer et al. (1989) studied the NIR variability for individual quasars using a sample of 108 optically selected sources. They showed that only half of their sources have a high probability of being variable. Enya et al. (2002a, 2002b, 2002c) analyzed the variability of 226 AGNs, in the $J$, $H$, and $K_s$ bands. Their work suggests that most AGNs are variable in the NIR. However, both studies have the following limitations: small number of epochs, limited redshift coverage, and only some specific classes of AGN were considered.

UltraVISTA (McCracken et al. 2012) is an ultra deep, NIR survey on the COSMOS field, using the 4 m VISTA survey telescope of the European Southern Observatory (ESO). UltraVISTA is repeatedly imaging the field in five bands ($YJHK_s$ and NB118), covering an area of 1.5 deg$^2$. The most recent UltraVISTA data release (DR3) corresponds to the first 5 yr of observations. We used individual OB (observation block) stacks, which are images corresponding to 0.5 or 1 hr of exposure, to perform an NIR AGN variability analysis. The advantage of these data compared to previous surveys is that UltraVISTA provides high-quality and good-resolution images (with a mean seeing of $\sim 0''.8$) at several epochs, as well as light curves with a length of almost 5 yr and with good sampling. Besides, the depth of the images allowed us to cover a wide redshift range, therefore allowing access to optical and NIR rest-frame emission.

In this work, we constructed light curves of known AGNs selected from public catalogs of the COSMOS field (Lusso et al. 2012; Muzzin et al. 2013; Laigle et al. 2016; Marchesi et al. 2016a), classifying them according to their X-ray, optical, and radio properties. We used these light curves to understand the differences in the variability behavior of the different classes of AGNs, by implementing statistical tools widely used by the AGN community, like the structure function, continuous-time first-order autoregressive process or CAR(1), and the excess variance.

This paper is organized as follows. In Section 2, we briefly introduce the data set and the public catalogs used. In Section 3, we give a definition of the different AGN classes considered in this work. In Section 4, we describe the steps needed to get the light curves. In Section 5, we explain all the statistical tools used for the variability analysis. In Section 6, we present the results of the different analyses, considering the whole data set and the different classifications. In Section 7, we discuss the physical implications of our work and summarize the main results. The photometry reported is in the AB system. We adopt the cosmological parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_L = 0.7$.

2. Data

2.1. NIR Data

Our work is based on the NIR imaging data from the UltraVISTA survey (McCracken et al. 2012), which has repeatedly imaged the COSMOS field during 5 yr in the $YJHK_s$ bands. The data considered in this work were taken between 2009 December and 2014 June, using the VIRCAM instrument on the VISTA telescope at Paranal (Dalton et al. 2006; Emerson et al. 2006; Sutherland et al. 2015). Further details of the data set can be found in McCracken et al. (2012).

The final products of the UltraVISTA survey are stacked images and their corresponding weight maps for each filter band. However, for our purpose, we worked with the individual OB stacks, which have a total exposure of 0.5 or 1 hr, produced by the Cambridge Astronomy Survey Unit (CASU) and provided by the survey team, from which we have constructed our light curves. The reduction process done by CASU includes dark subtraction, flat-fielding, sky-subtraction, and astrometric and photometric calibration; therefore, we did not implement any reduction steps with the exception of photometric calibration (see Section 4.1). The pixel scale of the images is $0''.34$ pixel$^{-1}$, and the average $5\sigma$ magnitude limits for the single images in each band are 23.3, 23.1, 22.2, and 22.1 for the $Y$, $J$, $H$, and $K_s$ bands, respectively.

2.2. Ancillary Data

We take advantage of the huge amount of ancillary data available for the COSMOS field, ranging from X-rays to radio waves. In our analysis we use four public catalogs.

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10 The survey also uses the NB118 band (Milvang-Jensen et al. 2013).
11 http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/data-processing
12 See Emerson et al. (2004), Irwin et al. (2004), Lewis et al. (2010), and Milvang-Jensen et al. (2013) for more details on the CASU processing steps.
The first one is a public $K_s$-selected catalog of the COSMOS/UltraVISTA field using the UltraVISTA data (Muzzin et al. 2013). This catalog provides photometry for 30 bands, covering the range 0.15–24 μm, besides other parameters related to the quality of the UltraVISTA photometry. For our work, the contamination parameter that resulted is particularly important, as it indicates whether an object’s photometry has been contaminated by a nearby bright star. When the value of this parameter is zero, there is no contamination.

The second one is the catalog of optical and infrared counterparts of the Chandra COSMOS-Legacy Survey (Marchesi et al. 2016a). This catalog contains 4016 X-ray sources from the 4.6 Ms Chandra program on 2.2 deg$^2$ of the COSMOS field (Civano et al. 2016), with 3877 sources having an optical/IR counterpart. The catalog provides X-ray fluxes measured in three bands (soft: 0.5–2 keV; hard: 2–10 keV; full: 0.5–10 keV), hardness ratios (HRs), intrinsic neutral hydrogen ($N_H$) column densities, luminosity distances, identification and photometry of the counterparts in $i$, $K_s$, and 3.6 μm, spectroscopic redshift and classification for 1770 sources, and photometric redshift and classification for 3885 sources, among other measurements. We complement the information of this catalog, with the new catalog of 1855 extragalactic sources in the Chandra COSMOS-Legacy survey catalog having more than 30 net counts in the 0.5–7 keV band (Marchesi et al. 2016b). This catalog provides new values of $N_H$ and the photon index ($\Gamma$) computed through spectral fitting. We use the values of $N_H$ reported by Marchesi et al. (2016b) when they are available; otherwise, we use the values reported by Marchesi et al. (2016a).

Besides, we used the COSMOS2015 catalog (Laigle et al. 2016), which provides photometric redshifts and stellar masses for more than half a million objects over 2 deg$^2$ in the COSMOS field, including photometry for several bands, with a wavelength coverage from the ultraviolet to the radio regimes. In particular, we used SuprimeCam $B$-band photometry (Taniguchi et al. 2007, 2015) and Very Large Array (VLA) photometry at 1.4 GHz (Schinnerer et al. 2004, 2007, 2010; Bondi et al. 2008; Smolčić et al. 2014).

Finally, Lusso et al. (2012) provide measurements of bolometric luminosities and Eddington ratios for X-ray-selected BL (382 sources) and NL (547 sources) AGNs from the XMM-Newton survey in the COSMOS field (Brusa et al. 2010). The bolometric luminosities are computed from the integrated SED.

The X-ray selection currently is the least biased but most expensive method to identify AGNs; thus, we considered as the base for our analysis the Marchesi et al. (2016a) catalog, as this allows us to work with sources securely classified as AGNs. We cross-matched this catalog with that of Muzzin et al. (2013), in order to secure the quality of the UltraVISTA photometry for every source, saving only the sources having a contamination parameter equal to zero. Then, we cross-matched the catalog with the Laigle et al. (2016) catalog, in order to obtain the $B$-band and radio photometry. Finally, the resultant catalog was cross-matched with the Lusso et al. (2012) catalog to obtain the bolometric luminosities for 718 of our sources. The final cross-matched catalog (hereafter the clean-AGN catalog) contains 3050 sources.

3. AGN Classification

Most of the variability studies available in the literature are based on objects classified as type I or unobscured AGNs (Cristiani et al. 1996; Nandra et al. 1997; Turner et al. 1999; Enya et al. 2002a, 2002b, 2002c; Vanden Berk et al. 2004; de Vries et al. 2005; Schmidt et al. 2010; Graham et al. 2014; Lanzuisi et al. 2014; Simm et al. 2016). Since we have well-sampled NIR light curves, we can expand our analysis and try to look for possible differences in variability between objects classified as obscured or unobscured according to different criteria. Using the information available from three public catalogs described in Section 2.2, we classified the sources of the clean-AGN catalog in the following way.

3.1. Spectroscopic Classification

Marchesi et al. (2016a) made use of the master spectroscopic catalog available for the COSMOS collaboration (M. Salvato et al. 2017, in preparation), to classify spectroscopically 1770 sources. For details on the source of the spectroscopic redshifts see Marchesi et al. (2016a). They classified the objects according to the following criteria:

1. BL: sources with at least one broad (FWHM $\geq$ 2000 km s$^{-1}$) emission line in their spectra (632 sources).
2. NL: sources that do not present BLs (they show narrow emission lines or absorption lines). These sources have not been separated between star-forming galaxies and type II AGNs because most of the sources have low signal-to-noise ratio spectra, or are in an observed wavelength range that does not allow to use emission line diagnostic diagrams to separate type II AGNs and star-forming galaxies (1049 sources).
3. Stars: sources spectroscopically identified as stars (89 sources).

From these subsamples, we have 563 BL AGNs and 952 NL AGNs in the clean-AGN catalog.

3.2. Photometric Classification

Marchesi et al. (2016a) also provide photometric redshifts and classification for 3885 objects. They used the method described by Salvato et al. (2011), which adjusts templates to the sources’ multiwavelength SEDs. The templates are divided into (Salvato et al. 2009) “unobscured AGNs,” which corresponds to a type I AGN or type I QSO template (894 sources); “obscured AGNs,” which corresponds to a type II AGN or type II QSO template (365 sources); “galaxy,” which corresponds to an elliptical, spiral, or starburst galaxy (2475 sources); and “star” (121 sources).

From these sources, in the clean-AGN catalog we have 688 unobscured AGNs, 295 obscured AGNs, 1944 galaxies, and 76 stars.

3.3. X-Ray Classification

Typically, AGNs are classified according to their X-ray obscuration by using the HR, $HR = (H - S)/(H + S)$ (where $H$ are the hard-band counts and $S$ the soft-band counts), or by the intrinsic hydrogen ($N_H$) column density. Since our sample has a wide dynamic range in redshift, we decided to use the $N_H$ provided by Marchesi et al. (2016b) (computed from spectral fitting) for the brightest sources and by Marchesi et al. (2016a)
(computed from the HR-z curve) for the faintest sources, instead of the HR, which is not corrected for redshift. We divided the sources between obscured and unobscured according to the following:

1. X-ray unobscured AGNs (XR I AGNs): objects with $0 \leq N_H < 10^{22}$ cm$^{-2}$.
2. X-ray obscured AGNs (XR II AGNs): objects with $N_H \geq 10^{22}$ cm$^{-2}$.

In the clean-AGN catalog we have 355 RL AGNs and 566 RQ AGNs.

### 3.4. Radio Classification

The COSMOS2015 catalog (Laigle et al. 2016) provides photometry in the SuprimeCam $B$ band (Taniguchi et al. 2007, 2015) and VLA fluxes at 1.4 GHz (Schinnerer et al. 2004, 2007, 2010; Bondi et al. 2008; Smolčić et al. 2014). We used this information to classify our sources as radio-loud (RL) and radio-quiet (RQ) using the ratio

$$R = \frac{L_v(5 \text{ GHz})}{L_v(4440 \text{ Å})},$$

(1)

where $L_v(5 \text{ GHz})$ is the radio luminosity of the source measured at 5 GHz and $L_v(4440 \text{ Å})$ is the $B$-band luminosity. Since the emission in the radio and optical regimes comes from the same source, it does not matter if we use directly the flux instead of the luminosity. We needed to apply a K-correction to the photometry provided by the COSMOS2015 catalog, since the values needed to calculate $R$ have to be in the rest frame. To do this, we considered that the radio and optical emissions follow a power-law like $F \propto \nu^{-0.8}$ and $F \propto \nu^{-0.44}$, respectively. Therefore, the final flux values used to determine $R$ are

$$F_v(5 \text{ GHz})_{\text{rest}} = F_v(1.4 \text{ GHz})_{\text{obs}} \left( \frac{1}{5} \right)^{0.8} (1 + z)^{-0.2}$$

$$F_v(4440 \text{ Å})_{\text{rest}} = F_v(4440 \text{ Å})_{\text{obs}} (1 + z)^{-0.56}.$$

(2)

In the COSMOS2015 catalog, not all sources have a detection at 1.4 GHz: for those sources without a detection reported, we assume that the measured flux corresponds to the 4$\sigma$ upper limit of 45 $\mu$Jy reported in Schinnerer et al. (2010). We then use the following criteria to classify our sources:

1. RL: the source has a real detection at 1.4 GHz and $R > 10$.
2. RQ: the source has $R < 10$, including upper limits and real detections at 1.4 GHz.

In the clean-AGN catalog we have 355 RL AGNs and 566 RQ AGNs.

### 4. Light-curve Construction

#### 4.1. Calibration and Photometry

For the construction of the light curves we used the time-resolved UltraVISTA images. These images were reduced using the CASU pipeline. The CASU stacks consist of 16 images, one per detector. Detector 16 is known for its unstable gain; therefore, we did not consider it in our analysis. We further point-spread function (PSF) homogenized the images and applied a photometric recalibration to match the UltraVISTA DR3 catalogs.

We perform a PSF homogenization, taking all the images of a certain filter band to a common seeing value, to avoid false variability detection, due to differences in seeing. Each image was convolved with a Gaussian of width equal to $\sqrt{(\sigma^2 - \sigma^2)}$, where $\sigma_0$ is the width corresponding to some of the worst seeing conditions, and $\sigma$ is the width of each individual image. Since the behavior of the seeing in the four filters is similar, we selected a fixed value of $\sigma_0 \sim 1''$ (or 2.95 pixels) for all the data sets and discarded all the images with a seeing worse than this value. The mean seeing value of the images is $\sim 0''.82$ for $J$, $H$, and $K_s$ and $\sim 0''.89$ for the $Y$ band. We discarded 17%, 10%, 8%, and 9% of the total images available for the $J$, $Y$, $H$, and $K_s$ bands, respectively.

With these new images, we proceeded with the source detection and photometry, using the public package SExtractor (Bertin & Arnouts 1996). We generate catalogs for every image in the four NIR bands. The catalogs contain the following for every source: position, aperture magnitude, and flux using an aperture of 2$''$; star classification (CLASS_STAR, given by the shape of the source); and the FLAG parameter, which informs whether an object is saturated or has been truncated at the edge of the image.

It is well known that SExtractor underestimates the photometric errors when there are correlated pixels and when the objects are dimmer than the background. Since the PSF homogenization produce correlated pixels, we calculated the photometric errors using a method similar to the one implemented by Gawiser et al. (2006). We estimated the photometric errors by placing 2000 random circular apertures of a certain size and measuring the number of counts ($F$) inside the apertures, taking care not to overlap the apertures with sources detected by SExtractor. We then calculated the standard deviation of the number of counts in the apertures. We repeated this procedure changing the size of the apertures from 1 to 14 pixels in aperture. We then modeled the standard deviation of $F$ as $\sigma_F = \sigma_0 N^a$, where $N = n_{\text{pix}}^{1/2}$, $n_{\text{pix}}$ is the number of pixels in the aperture, $\sigma_0$ is the standard deviation for an aperture of 1 pixel, and $a$ and $b$ are the parameters of the model. For every single image, we calculated the values of $a$ and $b$ and then calculated the final photometric error for every source as $\sigma_{\text{phot}} = \sqrt{\sigma_F^2 + F/gain}$, with $\sigma_F$ the number of pixels used in the aperture of 2$''$. The typical values of $\sigma_0$ are 1.0, 1.1, 3.5, and 2.0 for the $Y$, $J$, $H$, and $K_s$ bands, respectively. The values of $a$ and $b$ are $\sim 1.0$ and $\sim 1.6$, respectively.

Finally, we produced the calibrated catalogs. We used the catalogs generated by SExtractor and cross-matched them with the DR3 catalog for the corresponding photometric band. We selected all the sources classified as stars by SExtractor (CLASS_STAR $\geq 0.9$) and with good quality in their photometry (FLAG = 0) and took the difference between their measured magnitudes and the magnitudes according to the DR3 catalogs for the 2$''$ aperture. We then used a linear fit to model these residuals, following a procedure similar to Cartier et al. (2015), to prevent possible nonlinearities in the detector, which might be produced after the PSF homogenization, with $m - m_{\text{dr3}} = \alpha + \beta \times m$, where $m$ is the magnitude in our catalogs for a certain band and $m_{\text{dr3}}$ is the magnitude provided by the DR3 catalogs. Finally, the calibrated magnitudes ($m_{\text{cal}}$)

http://www.eso.org/sci/observing/phase3/data_releases/uvista_dr3.pdf
are computed as $m_{\text{cal}} = m - (\alpha + \beta \times m)$, and the calibrated errors as $\sigma_{\text{cal}} = \sqrt{\sigma_{\text{phot}}^2 + \text{var}}$, where var is the variance of $(m - m_{\text{cal}}) - (\alpha + \beta \times m)$. The typical values of $\alpha$ are $-0.55$, $-0.81$, $-1.42$, and $-1.91$ for the $Y$, $J$, $H$, and $K_s$ bands, respectively. For $\beta$ we normally have values of $\sim -0.0002$, $\sim -0.001$, $\sim -0.005$, and $\sim -0.009$ for the $Y$, $J$, $H$, and $K_s$ bands, respectively. Therefore, the nonlinearities of the detectors are negligible.

### 4.2. Light-curve Generation

We constructed light curves for all the sources in the clean-AGN catalog with a detection in the UltraVISTA single images. To construct the light curves, we cross-matched the clean-AGN catalog with every calibrated catalog, for which we knew their associated Julian dates, using a radius of 1". We discarded the outskirts of the images, considering only the regions with a distance greater than or equal to 0.015 to the border. We then constructed light curves for each source, saving only epochs where the SExtractor FLAG parameter was equal to zero. This prevents false detections of variability due to bad photometry. As a rule of thumb, we only saved those light curves with more than three epochs.

After this preliminary construction, we cleaned every light curve following a $\sigma$-clipping procedure. First, all the epochs with magnitude error bigger than twice the mean magnitude error were rejected. Second, we fitted an order five polynomial to the light curves and rejected all the epochs with a distance from the polynomial bigger than $2\sigma$, with $\sigma^2 = (\sigma_{\text{epoch}}^2 + \text{std})$, where $\sigma_{\text{epoch}}$ is the magnitude error in each epoch and std is the standard deviation of the whole light curve. Then, we only saved those light curves that ended with three epochs or more after the cleaning process. Finally, we transformed every light curve to the AGN rest frame: $t_{\text{rest}} = t_{\text{obs}} / (1 + z)$, where $t_{\text{rest}}$ is the light-curve time at the rest frame in days and $t_{\text{obs}}$ is the observed time. Every variability feature (see Section 5) was computed in the rest frame of the AGNs. We generated 1715, 1895, 1835, and 2107 light curves with magnitudes up to the $5\sigma$ limit in the $Y$, $J$, $H$, and $K_s$ bands, respectively. Figures 1 and 2 show examples of variable light curves in the four bands for objects classified as BL AGNs and NL AGNs.

The light curves are plotted in the observed frame. Figure 3 is an example of a nonvariable light curve. Figure 4 shows the mean error in magnitudes versus the mean magnitude for the final light curves. From the figure we can see that the $Y$ band has the best quality in the photometry and the $K_s$ band has the worst. This is expected, since as we move to redder bands, the sky brightness increases.

The UltraVISTA survey is split into two sets of strips called deep and ultradeep (see McCracken et al. 2012). In the first year of UltraVISTA both sets of strips were observed, thereby providing a nearly homogeneous coverage of the field. In the following 4 yr only the ultradeep strips were observed. This clearly influences both the number of epochs and the total length of the light curves for the objects in this study. Additionally, each strip consists of three pointings (pawprint positions), where each OB-obtained image was jittered around one such pawprint position. Therefore, we have light curves
with the number of epochs ranging from 3 to 365. Furthermore, the UltraVISTA project did not observe the COSMOS field in every photometric band by the same number of epochs. The band with the best-sampled light curves is the $K_s$ band, with a mean number of 92 epochs, followed by the $H$ band, with 85 epochs, the $J$ band, with 48 epochs, and finally the $Y$ band, with 45 epochs, on average. Figure 5 shows the number of epochs in the light curves. Most of the light curves have less than 50 epochs. Figure 6 shows the rest-frame time length ($t_{\text{rest}}$), defined as the length of the light-curve observed length divided by $(1+z)$. From the figure we can see that half of the light curves have a length of less than 200 days.

5. Variability Analysis

To characterize the variability of the sources, we used $P_{\text{var}}$, the excess variance ($\sigma_{\text{rms}}$), the structure function, and the continuous-time autoregressive process or CAR(1). The first two methods are used to detect the variability of a source, without taking into account the shape of the variation, while the last two methods can characterize the structure of the variability.

5.1. The $P_{\text{var}}$ Parameter

The $V$ parameter is defined by McLaughlin et al. (1996) as a value related to the probability of a source to be variable and is used in different variability studies (e.g., Paolillo et al. 2004; Young et al. 2012; Lanzuisi et al. 2014; Cartier et al. 2015). It is defined from the $\chi^2$ of the light curve:

$$\chi^2 = \sum_{i=1}^{N_{\text{obs}}} \frac{(x_i - \bar{x})^2}{\sigma_{\text{err},i}^2},$$

where $x_i$ is the magnitude at each epoch, $\sigma_{\text{err},i}$ is its error, $\bar{x}$ is the mean magnitude, and $N_{\text{obs}}$ is the number of epochs in which the object was detected. If the source were intrinsically nonvariable, the value of $\chi^2$ would be $\sim(N_{\text{obs}} - 1)$, the number of degrees of freedom in the data. To see whether the $\chi^2$ value is consistent with real variability, we calculate the probability $P_{\text{var}} = P(\chi^2)$ that a $\chi^2$ lower than or equal to the observed value could occur by chance for an intrinsically nonvariable source. If the value of $P_{\text{var}}$ is large, $1 - P_{\text{var}}$, the probability that the variability observed is due to Poisson noise alone and the source is intrinsically nonvariable is low. Therefore, we say that $P_{\text{var}}$ corresponds to the probability that the source is intrinsically variable. We then define the variability index as $V = -\log(1 - P_{\text{var}})$. Following Lanzuisi et al. (2014) and Cartier et al. (2015), we defined $P_{\text{var}} \geq 0.95$ (or $V \geq 1.3$) as our threshold to define a variable object.
Therefore, we might expect to detect 5% of false-positive sources.

5.2. The Excess Variance \( \sigma_{rms}^2 \)

The normalized excess variance \( \sigma_{rms}^2 \) (Nandra et al. 1997; Turner et al. 1999; Allevato et al. 2013; Lanzuisi et al. 2014; Cartier et al. 2015) is a measure of the variability amplitude. Here we adopt the definition

\[
\sigma_{rms}^2 = \frac{1}{N_{obs}} \sum_{i=1}^{N_{obs}} [(x_i - \bar{x})^2 - \sigma_{err,i}^2],
\]

and its error due to Poisson noise is

\[
\text{err}(\sigma_{rms}^2) = \frac{S_D}{x^2 N_{obs}},
\]

\[
S_D^2 = \frac{1}{N_{obs}} \sum_{i=1}^{N_{obs}} [(x_i - \bar{x})^2 - \sigma_{err,i}^2] - \sigma_{rms}^2.
\]

For a nonvariable object, the excess variance can be negative: if variability is not detected, due to large errors, the value of \( \text{err}(\sigma_{rms}^2) \) can be greater than \( \sigma_{rms}^2 \). The excess variance has to be treated with extreme care (Allevato et al. 2013), since it can be biased by the structure of the variability of the source, the sampling, and the length of the light curve. However, we only used the parameter to say whether a source has detected variability when \( (\sigma_{rms}^2 - \text{err}(\sigma_{rms}^2)) > 0 \), i.e., when the intrinsic amplitude of the variability (corrected by the photometric errors) is greater than zero. If a source accomplishes this criterion and has \( P_{var} \geq 0.95 \), we say that the object is intrinsically variable. This approach helps to reduce the fraction of false positives detected when we only consider the \( P_{var} \) parameter to classify an object as variable.

5.3. The Structure Function

The structure function describes the variability of a source by quantifying the amplitude of the variability as a function of the time lapse between compared observations \( (\tau) \) (Cristiani et al. 1996; Giveon et al. 1999; Vanden Berk et al. 2004; de Vries et al. 2005; Rengstorff et al. 2006; Schmidt et al. 2010; Palanque-Delabrouille et al. 2011; Graham et al. 2014; Cartier et al. 2015; Kozlowski 2016; Caplar et al. 2017). Kozlowski (2016) provides a good summary of the different definitions of the structure function used in the literature. In particular, he proposed to define it as \( \text{SE}_{1yr}(\Delta t) = 0.741 \times \text{IQR} \), where IQR is the interquartile range between 25% and 75% of the sorted \( y(t) - y(t + \Delta t) \) distribution. He also provides a method to measure the structure function taking into account the photometric noise: \( \text{SE}_{1yr}(\Delta t) = 0.549(\text{IQR}(\Delta t) - \text{IQR}(n)) \), where IQR(n) is the interquartile range between 25% and 75% of the sorted \( \Delta m \) for \( \Delta t < 2 \) days.

The structure function of AGNs is generally well described by a broken power law. The timescale were the break happens is known as the decorrelation timescale. Emmanoulopoulos et al. (2010) discussed the different limitations of the use of the decorrelation timescale as a physically meaning parameter, which can be severely affected by the light-curve sampling. Therefore, we limit our analysis to the regime were we can describe the structure function as a single power law (i.e., before the break):

\[
\text{SF}(\tau) = A \left( \frac{\tau}{1 \text{ yr}} \right)^\gamma,
\]

where \( A \) corresponds to the mean magnitude difference on a 1 yr timescale and \( \gamma \) is the logarithmic gradient of this change in magnitude.

The \( \gamma \) parameter is directly related to the PSD slope. When \( \text{SF} \propto \tau^\gamma \), then \( \text{PSD} \propto 1/\tau^{1+2\gamma} \); therefore, the value of \( \gamma \) changes depending on the type of process involved in the variation. For example, for a white-noise process \( \gamma = 0 \), and for a random walk process \( \gamma = 0.5 \).

Schmidt et al. (2010) provide two methods to define the structure function; the first one is similar to other definitions used in the literature:

\[
\text{SF}(\tau) = \frac{1}{N_{bin}} \sum_{i,j} \left( \frac{\pi}{2} |\Delta m_{ij}| - \sqrt{\sigma_i^2 + \sigma_j^2} \right),
\]

where the average \( |\Delta m_{ij}| \) is taken over all the epoch pairs \( i, j \) whose lag in time \( \Delta t_{ij} = t_j - t_i \) falls inside the bin \( [\tau - \Delta t, \tau + \Delta t] \). \( N_{bin} \) corresponds to the number of pairs inside the bin, \( \Delta m_{ij} \) is the difference in magnitude between the two epochs \( (m_i - m_j) \), and \( \sigma_i \) and \( \sigma_j \) are the magnitude errors for each epoch, respectively.

The second method proposed by Schmidt et al. (2010) is a Bayesian approach, where they model the structure function with a power-law using a Markov Chain Monte Carlo (MCMC) method. In this method, a list with all the possible epoch pairs is constructed. Then, the structure function is modeled considering a likelihood \( L(A, \gamma) \) and priors \( p(A) \) and \( p(\gamma) \) defined as

\[
L(A, \gamma) = \prod_{ij} \frac{1}{\sqrt{2\pi V_{eff,ij}}} \exp \left( -\frac{\Delta m_{ij}^2}{2V_{eff,ij}} \right),
\]

\[
V_{eff,ij}^2 = \left[ A \left( \frac{\Delta t_{ij}}{1 \text{ yr}} \right)^\gamma \right] + (\sigma_i^2 + \sigma_j^2),
\]

\[
p(A) \propto \frac{1}{A}, \quad p(\gamma) \propto \frac{1}{1 + \gamma^2}.
\]

The main advantage in determining the structure function with a Bayesian approach compared with traditional definitions is that it can avoid problems given by the sampling of the light curve and the selection of the bin size and shape, since these parameters are inferred directly from the data. This method is also less susceptible to windowing effects, given by the finite length of the light curve. Moreover, from the posterior distribution of the parameters, we can determine the mean value and the 1σ errors of the measurements. In our particular case, the values of \( \gamma \) and \( A \) were constrained to be in the ranges \( \gamma \in [0, 10] \) and \( A \in [0, 1] \) mag yr\(^{-1}\). Besides, we only considered epoch pairs with a maximum separation of 1 yr in the rest frame, in order to avoid the regime of the structure function after the break.

In order to test which of the previously mentioned methods is more suitable for the analysis of our data, we simulated artificial light curves with a power-law PSD and with a sampling representative of the UltraVISTA light curves in the Y band. To simulate the light curves, we used the algorithm proposed by Timmer & Koenig (1995). Then, we analyzed...
which method recovers the slope of the PSD more accurately. We simulated light curves with $\gamma = [0, 0.25, 0.5, 0.75, 1, 1.25]$. We generated 1000 light curves without photometric noise and 1000 light curves with a photometric noise of 0.02 mag. Light curves with the representative of our light curves in the $Y$ band for every value of $\gamma$. Figure 7 shows the results of this analysis. The left panel of the figure shows the results for the light curves without photometric noise. For all these light curves we were able to obtain measurements of the $\gamma$ parameter by using the three methods. However, it can be seen that the best results are obtained with the two methods proposed by Schmidt et al. (2010). The right panel of Figure 7 shows the results for the light curves with photometric noise. We were only able to obtain measurements of the structure function parameters for all light curves with the method of Kozłowski (2016) and with the Bayesian method of Schmidt et al. (2010). For the case of the analytic definition of the structure function proposed by Schmidt et al. (2010) (Equation (8)), $\sim 70\%$ of the light curves return “NAN” values of $\gamma$. These light curves are not considered in the results shown with red stars in the right panel of Figure 7. We think that this is a consequence of a too high subtraction of the noise term in Equation (8), as previously pointed out by Kozłowski (2016). Therefore, since the Bayesian method proposed by Schmidt et al. (2010) gives the best results and is more stable under the presence of photometric noise, we decided to use this method in the rest of our analysis. All the results presented below for the structure function were computed using the Bayesian method.

5.4. Continuous-time Autoregressive Process

The light curves of AGNs can be described by stochastic processes. In particular, Kelly et al. (2009) proposed that a continuous-time first-order autoregressive process or CAR(1) can be a good descriptor of this kind of variation. This model is also called “damped random walk,” since it is represented by a stochastic differential equation that includes a damping term that pushes the signal back to its mean:

$$dX(t) = -\frac{1}{\tau}X(t)dt + \sigma \sqrt{dt} \epsilon(t) + b dt, \quad \tau, \sigma, t > 0,$$

(12)

where $X(t)$ is the AGN light curve, represented by the observed magnitude, $\tau$ is the “relaxation time” of the process or the characteristic time for the time series to become roughly uncorrelated (related to the decorrelation time mentioned in the previous section), $\epsilon(t)$ is a white-noise process with zero mean and variance equal to 1, and $\sigma$ is the amplitude of the variability on short timescales compared with $\tau$. The mean value of the process is $b\tau$, and its variance is $\sigma^2\tau^2/2$. From the fit of a DRW process, we can derive the PSD of the light curve, avoiding the windowing effect that appears when the PSD is derived directly from the data:

$$\text{PSD}(f) = \frac{2\sigma^2\tau^2}{1 + (2\pi f\tau)^2},$$

(13)

where $f$ is the frequency measured in days$^{-1}$.

There are two main regimes for the PSD ($f$) of a DRW process. For short timescales (compared to the relaxation time, i.e., $f \lesssim (2\pi\tau)^{-1}$), the power spectrum falls off as $1/f^2$. On longer timescales than the relaxation time, the power spectrum flattens to white noise. Therefore, $\tau$ can be considered as the characteristic timescale of the variability (Kelly et al. 2009).

Several authors claimed that the AGN light curves can be modeled in a better way by CARMA models (Kelly et al. 2014; Simm et al. 2016). These models fully account for irregular sampling and measurement errors. CARMA models are generated by adding higher-order derivatives to the stochastic differential equation given in Equation (12). Kelly et al. (2014) provide a public PYTHON package to fit CARMA models called carma_pack. The package includes the option to model DRW processes.

Figure 7. Results of the structure function analysis for the artificial light curves with power-law PSD. In the $x$-axis we show the input value of $\gamma$, and in the $y$-axis we show the value of $\gamma$ computed by the different methods. The error bars in the $y$-axis correspond to the 15.86 and 84.14 percentiles of the output $\gamma$ distributions. The blue circles correspond to the results obtained using the definition given in Kozłowski (2016), the red stars correspond to the first definition given by Schmidt et al. (2010) (Equation (8)), and the yellow squares correspond to the Bayesian method proposed by Schmidt et al. (2010). The left panel corresponds to light curves without photometric noise. The right panel corresponds to light curves with a photometric noise of 0.02 mag. Light curves with “NAN” values of the $\gamma$ parameter are not included.

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14 https://github.com/brandonckelly/carma_pack
Kozłowski (2017) presents an analysis of the limitations of the DRW to model AGN light curves. He demonstrated that it is necessary to have light curves with at least 10 times the length of the “relaxation time” in order to have accurate variability parameters derived from the DRW analysis. We tested whether this effect is present when we use carma_pack to fit DRW models to our light curves. We simulated DRW light curves with a sampling representative of the light curves in the Y band, following the approach proposed by Kelly et al. (2009) using different values of τ, and then we fitted these light curves using carma_pack. We compared the output τ obtained from the method with the input τ used to generate the light curves. We define the parameter \( r = \log_{10}(\tau_{\text{out}}/\tau_{\text{in}}) \), where \( \tau_{\text{in}} \) is the length of the light curve. Figure 8 shows a comparison of \( \tau_{\text{in}} \) calculated using the input τ and \( \tau_{\text{out}} \) calculated using the output τ. In the figure we confirm the results of Kozłowski (2017). For light curves whose input τ is less than 10 times the length of the light curve, the output “relaxation time” is close to the original value. For the remaining light curves, the length is too short to give confident results. Since our light curves have a typical length of 5 yr, we would be able to detect accurately values of τ lower than ~180 days. After correcting by redshift, the length of most of our light curves is too short to measure τ accurately. Therefore, we decided not to include the DRW analysis in our results.

6. Results

We define a source as intrinsically variable, when its light curve has \( P_{\text{var}} > 0.95 \) and \( (\sigma_{\text{rms}} - \text{err}(\sigma_{\text{rms}})) > 0 \) (see Section 5.1 and 5.2). We found that 13.47%, 11.13%, 5.4%, and 6.22% of the total number of sources in the Y, J, H, and Ks bands, respectively, are variable. However, as shown in Figures 5 and 6, there are several light curves with poor sampling. Therefore, in order to homogenize our analysis, we only considered well-sampled light curves, that is, light curves with at least 20 epochs and with a rest-frame time length (\( t_{\text{rest}} \)) greater than or equal to 200 days. Besides, we only considered sources with either spectroscopic or photometric redshifts available (we use the best redshift reported by Marchesi et al. 2016a) and with a total \( K_s \) magnitude (equivalent to SExtractor “AUTO_MAG”) brighter than 22.0. We call this downsized sample the “clean sample.”

In this section we present the results of our variability analysis. Table 1 summarizes the number of light curves available for each object type in each NIR band before and after downsizing. The first value of every entrance in Table 1 corresponds to the results for the clean sample. The second value gives the numbers for the whole data set, before we downsized the sample. We found that 27.4%, 21.7%, 9.1%, and 11.5% of the sources from the clean sample in the Y, J, H, and \( K_s \) bands, respectively, are variable. As can be seen from the Table 1, we only miss a small fraction (~10%) of variable sources after the sample is downsized, while the relative fraction of variable sources doubles.

The Y and J bands have the best quality in the photometry (see Figure 4) and the larger fraction of variable sources. We will focus on the analysis of the clean sample in these bands in the following sections, unless otherwise noted.

Figure 9 shows the redshift distribution of the variable and nonvariable sources for the different classifications in the Y band. From the figure we can see that there are not important differences in the distributions of the variable and nonvariable sources, except for the radio classification, where we can see

### Table 1

| Classification | \( Y \) | J | H | \( K_s \) |
|----------------|--------|---|---|---------|
| Spectroscopic | 196/432 | 203/447 | 207/425 | 223/470 |
| BL | (152/129) | (64/67) | (79/83) |
| NL | 319/677 | 343/703 | 405/717 | 388/781 |
| (28/31) | (12/13) | (19/24) | |
| Type I | 205/465 | 211/488 | 216/442 | 237/503 |
| (159/130) | (67/70) | (81/87) | |
| Photometric Type II | 91/198 | 96/207 | 115/212 | 118/241 |
| (13/13) | (5/5) | (11/12) | |
| Galaxy | 478/564 | 637/663 | 1357 | |
| (1048) | (1196) | (1176) | |
| (34/46) | (64/24) | (25/32) | |
| X-ray | 368/793 | 395/837 | 450/814 | 455/907 |
| (153/161) | (63/65) | (81/87) | |
| XR I | 293/636 | 334/731 | 351/702 | 396/837 |
| (50/58) | (49/53) | (20/25) | (32/37) |
| Radio | 106/232 | 116/243 | 140/269 | 136/287 |
| (18/18) | (8/9) | (10/11) | |
| RL | 185/408 | 183/392 | 231/436 | 210/439 |
| (118/128) | (58/65) | (71/77) | |
| RQ | 175/385 | 185/392 | 231/436 | 210/439 |
| (213/231) | (88/99) | (117/131) | |

Note. In parentheses we show the number of variable sources.
that the nonvariable sources are clustered at lower redshifts. This is produced by the spectroscopic classification of the sources with radio classification, since most of the nonvariable sources are NL and are located at low redshifts and most of the variable sources are BL and are located at higher redshifts.

6.1. Variability Properties

Figure 10 shows the distribution of the power-law parameters of the structure function $A$ and $\gamma$, for the variable sources in the $Y$ and $J$ bands in logarithmic scale. We mark the sources according to their spectroscopic and X-ray classifications. Histograms at the top and right-hand side of the plots better represent the normalized distributions of variable sources of different AGN populations.

The mean and $1\sigma$ errors of the structure function parameters for the variable sources are $A_Y = 0.15^{+0.16}_{-0.07}$ and $\gamma_Y = 0.62^{+0.42}_{-0.32}$ for the $Y$ band and $A_J = 0.13^{+0.12}_{-0.08}$ and $\gamma_J = 0.63^{+0.56}_{-0.29}$ for the $J$ band. Clearly several sources have values of $\gamma$ consistent with a DRW process. However, there are some sources with $\gamma > 1.0$ (36 and 43 for the $Y$ and $J$ bands, respectively), which implies deviations from a DRW process ($\gamma = 0.5$). These results are consistent with previous analyses, which have found that CARMA models with higher orders (and not a simple DRW model) better describe AGN light curves (e.g., Kasliwal et al. 2015, 2017; Simm et al. 2016).

From Figure 10 we can see that the distribution of the $A$ parameter has a noticeable difference when we compare the sources classified as BL and NL, in particular in the $Y$ band. On the other hand, when we compare the XR I and XR II sources, the difference is less evident. In order to have a more quantitative comparison of the structure function parameter distributions, we performed a two-sample Anderson–Darling test (Pettitt 1976) for the $A$ and $\gamma$ parameters considering the spectroscopic and X-ray classification. Since the Anderson–Darling test does not take into account the errors of the parameters, we only considered in the test those variable sources with a measured parameter having a signal-to-noise ratio higher than 3, considering as the error of the parameter the average of the lower and upper errors given by the Bayesian analysis. According to the test, for the BL and NL, the distributions of the $A$ parameter are different at a 99.5% significance level in both the $Y$ and $J$ bands, with a $p_{\text{value}}$ of $8.99 \times 10^{-6}$ and $1.69 \times 10^{-4}$ for the $Y$ and $J$ bands, respectively. For the XR I and XR II sources, no statistically significant difference is found for the $A$ parameter, with a $p_{\text{value}}$ of 1 and 0.87 for the $Y$ and $J$ bands, respectively. For the case of the $\gamma$ parameter, no statistically significant differences are found in any filter for the spectroscopic and X-ray classifications. The $p_{\text{value}}$ are 0.052 and 0.076 for the $Y$ and $J$ bands, respectively, in the spectroscopic classification and 0.48 and 0.16 for the $Y$ and $J$ bands, respectively, in the X-ray classification.

Since the dynamic range in redshift considered in this analysis is wide, we repeated the analysis selecting the smallest bin of redshift where we can ensure the presence of at least six sources belonging to every population (BL, NL, XR I, and XR II), in order to have confident results from the Anderson–Darling test. This requirement is accomplished by the bin of redshifts between 0.3 and 1 (see Figure 9). In this bin we expect to observe emission coming from the accretion disk in both $Y$ and $J$ bands. The results of the Anderson–Darling test are the same. The distributions of the $A$ parameter for the spectroscopic classification are different at a 99.5% significance level in both $Y$ and $J$ bands, with a $p_{\text{value}}$ of 0.01 and 0.03, respectively. For the case of the $A$ parameter in the X-ray classification ($p_{\text{value}}$ of 0.22 and 0.1) and the $\gamma$ parameter in both classifications (spectroscopic: $p_{\text{value}}$ of 0.41 and 0.40; X-ray: $p_{\text{value}}$ of 0.39 and 0.23), no statistically significant differences are found in any filter.

Figures 1 and 2 show examples of light curves that are variable in the four photometric bands. We plotted the light curves of these two sources because they are particularly interesting. In Figure 1 the source is classified as BL-XR II. On the other hand, in Figure 2, the source is classified as NL-XR II. Even though this source is NL and obscured in the X-ray regimes, we can detect its variation in the four photometric bands. Its variability parameters in the $Y$ filter band are $A = 0.05$ (mag yr$^{-1}$) and $\gamma = 0.69$. This source could potentially be an example of “changing look” AGNs.

6.2. Dependency with Redshift and Luminosity

Redshift will obviously change the rest-frame emission observed by each band. Any correlation with redshift, therefore, needs to take this into account. Besides, previous analyses have shown evidence of an anticorrelation of optical/UV luminosity with the variability amplitude (e.g., Uomoto et al. 1976; Hook et al. 1994; Trevese et al. 1994; Cristiani et al. 1997; Wilhite et al. 2008; Kelly et al. 2009; MacLeod et al. 2011; Meusinger & Weiss 2013; Simm et al. 2016; Caplar et al. 2017).
words, a more luminous (and probably larger) system varies, at a given fractional amplitude, on larger timescales.

In order to test any possible correlation of the structure function parameters with luminosity, we used bolometric luminosities ($L_{\text{BOL}}$) from Lusso et al. (2012). We also test any correlation with the intrinsic hard X-ray luminosity ($L_{\text{HL}}$; i.e., rest-frame luminosity corrected by absorption), using the X-ray data from Marchesi et al. (2016a). The value of $L_{\text{HL}}$ was computed using the rest-frame observed luminosity ($L_{\text{obs}}$) and the luminosity absorption correction ($k_{\text{corr}}$) provided by Marchesi et al. (2016a): $L_{\text{HL}} = L_{\text{obs}} / k_{\text{corr}}$. We tested the correlations with luminosity and redshift for those variable sources with measured values of both $L_{\text{BOL}}$ and $L_{\text{HL}}$, which corresponds to 139 and 123 sources in the $Y$ and $J$ bands, respectively.

We calculated the Spearman rank-order correlation coefficient $r_s$ for log($A$) versus log($1+z$) and for log($\gamma$) versus log($1+z$) in the $Y$ and $J$ bands. We find clear evidence of positive correlation between $A$ and ($1+z$). The values of the coefficient for the correlation between $A$ and ($1+z$) are $r_s = 0.47$ ($p_{\text{value}} = 5.5 \times 10^{-5}$) and $r_s = 0.54$ ($p_{\text{value}} = 1.4 \times 10^{-10}$) for $Y$ and $J$ respectively. For the case of log($\gamma$) versus log($1+z$), the correlation is not evident. The values of the Spearman rank-order correlation coefficients are $r_s = 0.08$ ($p_{\text{value}} = 0.38$) and $r_s = 0.1$ ($p_{\text{value}} = 0.29$) for $Y$ and $J$, respectively.

For the case of $L_{\text{BOL}}$, the Spearman coefficient showed some evidence of a positive correlation between log($A$) and log($L_{\text{BOL}}$), contrary with what was expected from previous analyses. The values of the coefficient are $r_s = 0.3$ ($p_{\text{value}} = 3.7 \times 10^{-4}$) and $r_s = 0.3$ ($p_{\text{value}} = 6.6 \times 10^{-4}$) for $Y$ and $J$, respectively. However, this result might be affected by the wide dynamic range in redshift considered in the sample ($z \sim 0.3-4$). Thus, in order to disentangle whether the positive correlation is driven by redshift or by luminosity, further analysis is needed. Moreover, the correlation analysis showed no evidence of correlation between log($\gamma$) and log($L_{\text{BOL}}$). The coefficients are $r_s = 0.08$ ($p_{\text{value}} = 0.32$) and $r_s = -0.04$ ($p_{\text{value}} = 0.65$) for $Y$ and $J$, respectively.

Finally, for the case of $L_{\text{HL}}$, the correlation coefficient showed a weak positive (or nonpositive) correlation between log($A$) and log($L_{\text{HL}}$), with $r_s = 0.19$ ($p_{\text{value}} = 0.024$) and $r_s = 0.15$ ($p_{\text{value}} = 0.093$) for $Y$ and $J$, respectively. On the other hand, for log($\gamma$) and log($L_{\text{HL}}$), the correlation is negligible, with $r_s = 0.01$ ($p_{\text{value}} = 0.9$) and $r_s = 0.01$ ($p_{\text{value}} = 0.87$) for $Y$ and $J$, respectively. Similar to the case of $L_{\text{BOL}}$, we need further analysis to say whether the correlation between log($A$) and log($L_{\text{HL}}$) is affected by the wide dynamic range in redshift.

To test whether the positive correlation of the amplitude of the structure function with luminosity can be due to a positive correlation with redshift, we calculated the correlation of $A$ with both $L_{\text{BOL}}$ and redshift in the logarithmic space, i.e., we computed

$$\log_{10}(A) = a \log_{10}(L_{\text{BOL}}/10^{45} \text{ erg s}^{-1}) + b \log_{10}(1+z) + c$$

for the same sources considered in the previous analysis. For this purpose, we computed the weighted least-squares linear regression (WLS), considering as weights the inverse of the variance of log($A$), calculated as

$$\sigma^2(\log_{10}A) = (0.434 \times (A_{\text{loerr}} + A_{\text{uperr}})/24)^2.$$ A summary of the regression for the $Y$ and $J$ filter bands can be found in Table 2. From the table, we can see that the correlation between log($A$) and log($L_{\text{BOL}}$) is in fact negative and is statistically significant but weak, and the correlation between log($A$) and log($1+z$) is positive and significant. Therefore, the positive

Figure 10. Distribution of the structure function power-law parameters $A$ and $\gamma$, for the variable sources, in the $Y$ and $J$ bands, in logarithmic space. The blue symbols correspond to BL AGNs, the red symbols to NL AGNs, and the yellow symbols to sources without spectroscopic classification. The circles correspond to XR I AGNs, the triangles to XR II AGNs, and the stars to sources without X-ray classification. The errors of the measurements are shown with gray error bars. For most of the sources, the size of the error bars is smaller than the marker size. Along the axes we show the projected $A$ and $\gamma$ distributions for the BL AGNs (blue shaded), NL AGNs (red shaded), XR I AGNs (blue hatched), and XR II AGNs (red hatched).
correlation between \( \log(A) \) and \( \log(L_{\text{BOL}}) \) obtained using the Spearman coefficient was actually an effect of the positive correlation with redshift. Thus, whenever we perform a correlation analysis for the luminosity, we need to consider the redshift of the source as a second independent variable.

In Table 2 we can also see the results for the regression of \( A \) with both \( H_{\text{Lint}} \) and redshift in the logarithmic space. In this case, we computed

\[
\log_{10}(A) = a \log_{10}(H_{\text{Lint}}/10^{44}\text{erg s}^{-1}) + b \log_{10}(1+z) + c.
\]

The results of the WLS analysis show that the correlation with \( H_{\text{Lint}} \) is not statistically significant in any band. Therefore, the weak positive correlation observed in the previous analysis might be produced by the positive correlation with redshift.

The positive correlations with redshift are consistent with observing bluer regions of the AGN SED as redshift increases, as bluer emission is expected to vary with larger amplitude. Figure 11 shows \( A \) versus rest-frame wavelength of emission (\( \lambda \)) at logarithmic scale for the variable sources, in the \( Y \) and \( J \) bands. There is a clear anticorrelation between \( A \) and \( \lambda \), and the results of the linear regression for the \( Y \) and \( J \) bands are consistent at 95% level. However, there is a large dispersion in the correlation. This can be related to other properties of AGNs that may affect the amplitude of the variability aside from the emission wavelength, such as the bolometric luminosity (which, as we already demonstrated, anticorrelates with the amplitude of the variability), the black hole mass, and the accretion rate, among other physical properties, as well as the length and quality of the light curves, among observational factors.

The lack of correlation between \( \gamma \) and redshift might indicate that the structure of the variability is independent of wavelength. This is consistent with previous analyses of optical and NIR light curves that claim that light curves of AGNs observed at different wavelengths have the same structure or shape in timescales of months to years, but showing time lags between them, due to the distance between the emitting regions, and showing a decrement in the amplitude of the variation (Lira et al. 2011, 2015).

Figure 12 shows the absolute magnitude for the variable sources (not \( k \)-corrected) versus redshift (bottom axis) and versus rest-frame wavelength of emission, for the \( Y \) band (top axis). In the figure we mark those sources according to their spectroscopic and X-ray classifications, as before. At the bottom of the figure we show the fraction of variable BL and NL sources in logarithmic scale. The number of variable NL sources in logarithmic scale. The number of variable NL

### Table 2

| Filter | Luminosity | \( a \) | \( b \) | Intercept |
|--------|------------|--------|--------|-----------|
| \( Y \) | \( L_{\text{BOL}} \) | \(-0.11 \pm 0.05\) | \(1.38 \pm 0.29\) | \(-1.22 \pm 0.1\) |
| \( Y \) | \( H_{\text{Lint}} \) | \(-0.05 \pm 0.03\) | \(1.14 \pm 0.26\) | \(-1.12 \pm 0.1\) |
| \( J \) | \( L_{\text{BOL}} \) | \(-0.13 \pm 0.03\) | \(1.85 \pm 0.26\) | \(-1.42 \pm 0.09\) |
| \( J \) | \( H_{\text{Lint}} \) | \(0.003 \pm 0.03\) | \(1.52 \pm 0.24\) | \(-1.38 \pm 0.09\) |

**Note.** \( p \)-values are shown in parentheses.
sources detected at $0.5 \mu m < \lambda_{\text{rest}} < 1 \mu m$ is low ($\lesssim 10\%$). However, since this wavelength range is expected to be dominated by emission from the accretion disk and not directly observable in most of the obscured systems, we would not expect to detect high variability from NL sources in this regime. These sources, however, do not show the same variability properties as their BL counterparts, and they cluster at significantly smaller values of $A$ and $\sigma$ in Figure 10.

As torus emission is not expected around rest frame $0.5 \mu m$, the most likely explanation is that these variable NL sources correspond to BL AGNs, but where the host galaxy might be damping the variability signal (hence yielding smaller values of the parameter $A$), and masking the presence of weak BLs in the spectra. One way to check this is by looking at the intrinsic X-ray luminosity in the hard band (rest-frame luminosity and corrected for absorption), for variable BL and NL AGNs. This is presented in Figure 13. It clearly shows that most of the NL variable sources have low luminosity ($\text{HL}_{\text{int}} < 10^{44} \text{ erg s}^{-1}$). We therefore discard “true type II” AGNs as a possibility to explain our low-luminosity variable NL sources, since we might expect to observe that their variability properties, like the structure function parameters, are similar to the properties of normal BL sources, which is not seen for most of our variable NL sources. For the case of the few bright NL variable sources, we cannot discard that they are “true type II” AGNs.

To have a better understanding of the nature of these variable NL sources, we plot in Figure 14 a histogram of $\text{HL}_{\text{int}}$ for the NL variable sources, split by their photometric classification. From the figure we can see that most of the low-luminosity sources were adjusted by a galaxy template in Marchesi et al. (2016a). This result supports our idea that most of the low-luminosity variable NL sources correspond to BL sources whose emission is overshadowed by their host galaxy. However, a few sources have a photometric classification of type I. These sources can be either “true type II” AGNs or normal BL sources whose optical spectrum does not sample the region where the BL sources are present, since the SED analysis reveals a continuum emission that is consistent with continuum emission of BL sources.

**Figure 13.** Histogram of the intrinsic luminosity (rest frame and corrected for absorption) in the hard X-ray band, of variable sources in the $Y$ band, considering the spectroscopic classification. BL sources are shown in blue and NL sources in red.

**Figure 14.** Histogram of the intrinsic luminosity (rest frame and corrected for absorption) in the hard X-ray band, of variable NL sources in the $Y$ band, split by their photometric classification. NL-type I are shown in blue, NL-type II in red, and NL-Gal in yellow.

### 6.3. Fraction of Variable Sources

In this section we show the results of our variability analysis considering the fraction of variable sources. The results shown in this section are for the four photometric bands. Figure 15(a) shows the fraction of variable sources for BL AGNs and NL AGNs (also see Table 1). We can see that BL AGNs have a higher fraction of sources with detected variability in comparison with NL AGNs. Besides, we can see a decrement in the fraction of variable BL AGNs as we move to redder bands. This can be related to the increment of the photometric errors from the $Y$ to $K_s$ bands. However, we also have to consider that for centrally driven variations it is expected that the amplitude of the variability is lower at longer wavelengths, and therefore we might expect to have a reduction in the fraction of variable sources detected as we move to longer wavelengths. This is in fact observed in BL AGNs, where the fraction of variable sources reduces systematically from the $Y$ to the $H$ band. The increase observed in the $K_s$ band could be accounted for by the presence of the torus, which has a large solid angle as seen by the innermost region of the disk, hence boosting its variability.

For the case of NL AGNs we observe that the fraction of variable sources is above 5% only for the $Y$ and $J$ bands. In the context of the unified model, we might expect a very low probability to detect variable sources for the $Y$ and $J$ bands and an increment in the fraction for the $H$ and $K_s$ bands. However, some optical variability might be expected for NL sources considering that the obscuring material is a distribution of moving clumps or clouds. Besides, as mentioned in Section 3.1, the classification of NL sources considers the lack of visible broad emission lines. For the case of BL sources located at redshift $\sim 1$, depending on the spectral coverage, the typical BL components might be out of the spectra and therefore be classified as NL. For these sources, we might expect to detect optical variability.

For the case of the photometric classification, we show in Figure 15(b) the fraction of variable sources in the four photometric bands (also see Table 1). We can see that the highest fraction of variable sources is for the type I objects. They have a similar fraction of variable sources to BL AGNs.
The fraction of type II variable sources is lower than that of type I sources, but slightly larger than that of NL AGNs. Sources classified as “Galaxies” show the lowest fraction of variability. It is important to notice that for most of the sources best-fitted with a galaxy template by Marchesi et al. (2016a), the X-ray luminosity is $>10^{42}$ erg s$^{-1}$, and therefore the sources are most likely AGNs, although their optical–IR SED does not clearly show this. As before, variability is revealing unobscured AGNs in sources where an SED analysis predicts otherwise.

We show in Figure 15(c) the fraction of variable sources for the X-ray classification (also see Table 1). From the figure we can notice that XR I objects have a larger fraction of variable sources than XR II objects. Another obvious result is the lower fraction of X-ray classified variable sources when compared with those with an optical classification. This is not a luminosity effect. In fact, the mean of the X-ray luminosity of the X-ray sample is $10^{43.4 \pm 0.7}$ erg s$^{-1}$, while the same value for the subsample with optical spectroscopy corresponds to $10^{43.5 \pm 0.7}$ erg s$^{-1}$. We also checked whether this result is related to the method used to separate obscured and unobscured X-ray sources. We repeated the analysis separating the sources by their HR. We considered a source as unobscured in X-rays if $< -H_{0.2}$. We obtained similar results to the ones showed in Figure 15(c). Therefore, this result is not produced by the definition of X-ray obscuration used.

To understand in a better way this difference, we plot in Figures 16(a) and (b) the fraction of variable sources, considering the X-ray and spectroscopic classification and the X-ray and photometric classification, respectively. From the figures, we can see that the difference in the fraction of variable sources is more closely related to the optical obscuration of the sources than to the X-ray obscuration. Sources unobscured in the optical range are the ones with the largest fraction of variable objects, irrespective of their X-ray classification. In fact, sources classified as unobscured in the X-rays but obscured in the optical range (NL-XR I or Type II-XR I) have a lower fraction of variable objects than sources classified as obscured in the X-rays and unobscured in the optical range (BL-XR II or Type I-XR II). As a significant fraction of XR I sources have an NL classification (136/368,142/395, 175/450, and 159/455, in the $Y$ to $K_s$ bands, respectively), this explains the low fraction of variable sources classified as unobscured in X-rays. We repeated the analysis separating the sources by their HR. Again, we obtain similar results, and therefore our results are not biased by the definition of X-ray obscuration. We also repeated the analysis for the redshift bin $z \sim 0.3–1.0$, and the results were consistent with what we found for the whole sample.

These results might be related to the differences in the origin of the obscuration in the optical and X-ray regimes. Marchesi et al. (2016b) analyzed the X-ray spectral properties for a subsample of the Chandra COSMOS-Legacy Survey catalog and showed that most of the sources classified as BL-XR II have $L_{\geq 10 \text{keV}} > 10^{44}$ erg s$^{-1}$. They conclude that the existence of these objects suggests that optical and X-ray obscuration can be caused by different mechanisms and that the X-ray obscuration might be due to dust-free material surrounding the inner part of the nuclei. Merloni et al. (2014) presented a detailed discussion on the nature of sources that have inconsistent classification in the optical and X-ray regimes.
They found that sources classified as BL-XR II (type-12 in Merloni et al. 2014) tend to have higher luminosities. Additionally, they showed that the main differences between sources classified as BL-XR II and sources classified as BL-XR I (or type-11) happen in the X-ray regime. They demonstrated that the optical spectra and the SED of these two populations do not show substantial differences, and they proposed that the excess absorption in the X-ray regime presented in the type-12 sources could be produced by dust-free material within (or inside) the BLR. Our variability analysis strengthens this idea, since we do not observe significant differences in the variability features and in the fraction of variable sources between the BL-XR I and BL-XR II populations.

Marchesi et al. (2016b) showed that most of the sources classified as NL-XR I have $L_{2-10keV} < 10^{33}$ erg s$^{-1}$, and they expected a fraction of these sources to be “true type II” AGNs. Merloni et al. (2014) found that the sources classified as NL-XR I (or type-21) tend to have lower luminosities, $L_X < 10^{44}$ erg s$^{-1}$, and that their composite spectrum and SED reveal evidence of host galaxy dilution. They proposed that a minority of these objects could be “true type II” AGNs. Our variability analysis agrees with the findings of Merloni et al. (2014), since of the 18 sources classified as variable NL-XR I in the $Y$ band, 10 have photometric classification of Galaxy, 4 are Type II, and 4 are Type I. Therefore, these 10 NL-XR I-Galaxy sources can be a clear example of BL sources with host galaxy dilution, but whose variability can be detected. The four NL-XR I-type I sources can be examples of optically obscured variable sources.

Figure 17 shows the fraction of variable sources for the radio classification. In this case, the RQ sources show a considerably higher fraction of variable sources than the RL sources. A total of 72% of the RL sources and 60% of the RQ sources are classified as NL AGNs. The large fraction of RL objects with an NL classification is not surprising. RL objects represent a distinctive AGN population not only because of their radio properties. They are also characterized by massive hosts, large BH masses, and very accretion rates (Heckman & Best 2014, and references therein). These traits seem to suggest that these are systems at the end of their life cycles of actively growing BH masses. The very low Eddington ratios in turn would be replaced by an advection-dominated or radiatively inefficient accretion flow (ADAFs/RIAFs; Narayan & Yi 1994, 1995; Blandford & Begelman 1999). The absence of a classical accretion disk, and most likely of a classical BLR, would explain the spectroscopic classification of the RL sources and of the observed lack of variability. In this scenario, the lack of significant variability would not be due to obscuration, but to the intrinsic nature of these extremely low accreting sources.
7. Discussion and Conclusions

In this paper we present a characterization of AGN variability in the NIR regime, using data from the UltraVISTA survey (McCracken et al. 2012). UltraVISTA repeatedly imaged the COSMOS field in five bands (YJHK$_s$ and NB118), covering an area of 1.5 deg$^2$, to achieve a very deep final image. The survey provides excellent-quality, high spatial resolution data (with a mean seeing of $\sim0''8$) at different epochs and has allowed us to analyze NIR variability within a time span of almost 5 yr with good sampling. Besides, the depth of the images allows us to cover a wide redshift range, accessing the optical and NIR rest-frame emission. We used our data.

we observed damped variability for both BL and NL AGNs. The photometric bands used in our analysis (YJHK$_s$) allowed us to access optical and NIR rest-frame emission, depending on the redshift of the source and the band considered. These two access optical and NIR rest-frame emission, depending on the unobscured sources; however, there are some cases where our data.

fore increasing the fraction of variable sources. This is seen in the median flux density of the optical rest-frame range that most of them, which are also characterized by low AGN luminosities, correspond to BL AGNs whose host galaxy is damping the variability signal, since most of them have a photometric classification of “Galaxy.” We also proposed in Section 6.3 that the four sources with variability properties similar to BL, with photometric classification of type I, unobscured in X-rays and with high luminosities, correspond to “true type II” AGNs or to BL AGNs whose spectrum does not cover the region where the BL sources are present. For the case of the four variable sources classified as NL-type II sources in the Y band, we propose that they are examples of variable optically obscured sources.

The regression analysis of the structure function parameters with redshift and $L_{BOL}$ (Section 6.2) showed that $A$—related to the amplitude of the variability in a timescale of 1 yr—has a positive correlation with redshift and a weak anticorrelation with $L_{BOL}$. These results are in agreement with previous analyses (e.g., Simm et al. 2016; Caplar et al. 2017). On the other hand, the correlation between $A$ and $HL_{int}$ is not statistically significant. The correlation of the amplitude of the variability with redshift reveals an anticorrelation of the amplitude with the wavelength of emission. As we move to redder bands, the amplitude of the variability decreases (see Figure 11).

For the case of the parameter related to the structure of the variability, $\gamma$, the results of our analysis in Section 6.2 did not show any correlation with redshift, $L_{BOL}$, or $HL_{int}$. We also showed in Section 6.1 that several sources have values of $\gamma$ consistent with DRW processes; however, there are a non-negligible number of variable sources with $\gamma > 1.0$ (36 for the Y band and 43 for the J band), which reveals deviations from a simple DRW process.

We also showed in Section 6.3 that the fraction of variable sources unobscured in the X-ray is lower than the fraction of variable sources unobscured in the optical (in the spectroscopic and photometric classifications). We demonstrated that when we split the sources by their spectroscopic and X-ray classifications and by their photometric and X-ray classification (Figure 16), the differences in the fraction of variable sources are given by optical obscuration (i.e., spectroscopic and photometric classifications) and not by X-ray obscuration (X-ray classification). In other words, optical rest-frame variability is indifferent to X-ray obscuration. We think that an explanation is that optical and X-ray obscurations are caused by different mechanisms, and that X-ray obscuration might be due to dust-free material surrounding the inner part of the nuclei, as was proposed by Merloni et al. (2014) and Marchesi et al. (2016b).

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