



Understanding high redshift Active Galactic Nuclei activity through infrared variability

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A surprise >:D

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Abstract

Abstract

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ensuring I was doing something but never caring what it was. Your gentle encouragement lead me beyond the stars.

Equality Diversity and Inclusion

Published works

The majority of the material presented in this thesis has already been published in — or is in preparation for submission to — as the following works:

- I **Green K.**, Elmer, E., Maltby, D., Almaini, O., Merrifield, Hartley W. G., 2024, MNRAS, —: ‘*Increasing AGN sample completeness using long-term near-infrared variability*’.
- II **Green K.**, Elmer, E., Maltby, D., Almaini, O., Merrifield, Hartley W. G., in prep, —: *Paper 2*.

The vast majority of work presented here was carried out by the author, with advice from the paper authors above. Where the work contains the product of larger collaborations, this is mentioned in the relevant chapter.

Chapter 1

Introduction

1.1 Extragalactic Astronomy

It is now well understood that the Milky Way is just one of many galaxies in the Universe, however this was not always known. In western 18th century astronomy, the Milky Way was considered the extent of the universe itself, however the philosopher Immanuel Kant presented the idea of other galaxies with his “island universes” theory as an explanation for the observed “nebulae of unknown nature” (The Andromeda Galaxy). This “Great Debate” ([Curtis, 1988](#)) as to whether these systems existed within the Milky Way continued until the early 20th century, where Hubble was able to calculate the distance to one such spiral nebulae and proved they were truly extra galactic in nature ([Hubble, 1925](#)).

This discovery launched the field of extragalactic astronomy, as the obvious questions into to the nature of these other galaxies arose.

As observations of galaxies were taken, it was quickly found that they have a range of complexity in their structure. A well-known outcome from the attempts in sorting these galaxies is the Hubble sequence ([Hubble, 1926](#)). This sequence was initially built as a means to categorise galaxies from less to more complex systems, with Hubble noting that the "early" and "late" type labels referred to their position in the series, and had no reflection on the actual evolution of the system. As scientific research progressed and more information became available, Hubble set out to update his initial classification system, but was unable to finish this work before his death. As such, [Sandage 1961](#) was able to update this work into the Hubble Tuning Fork classification for galaxies that is popular today. (Figure1.1).

1.2 Active Galaxies

1.2.1 Black Holes

Beyond the visual, morphological observations in galaxies, further discoveries into their structure were found. Crucially, it was found that most, if not all galaxies contain a supermassive black hole (SMBH).

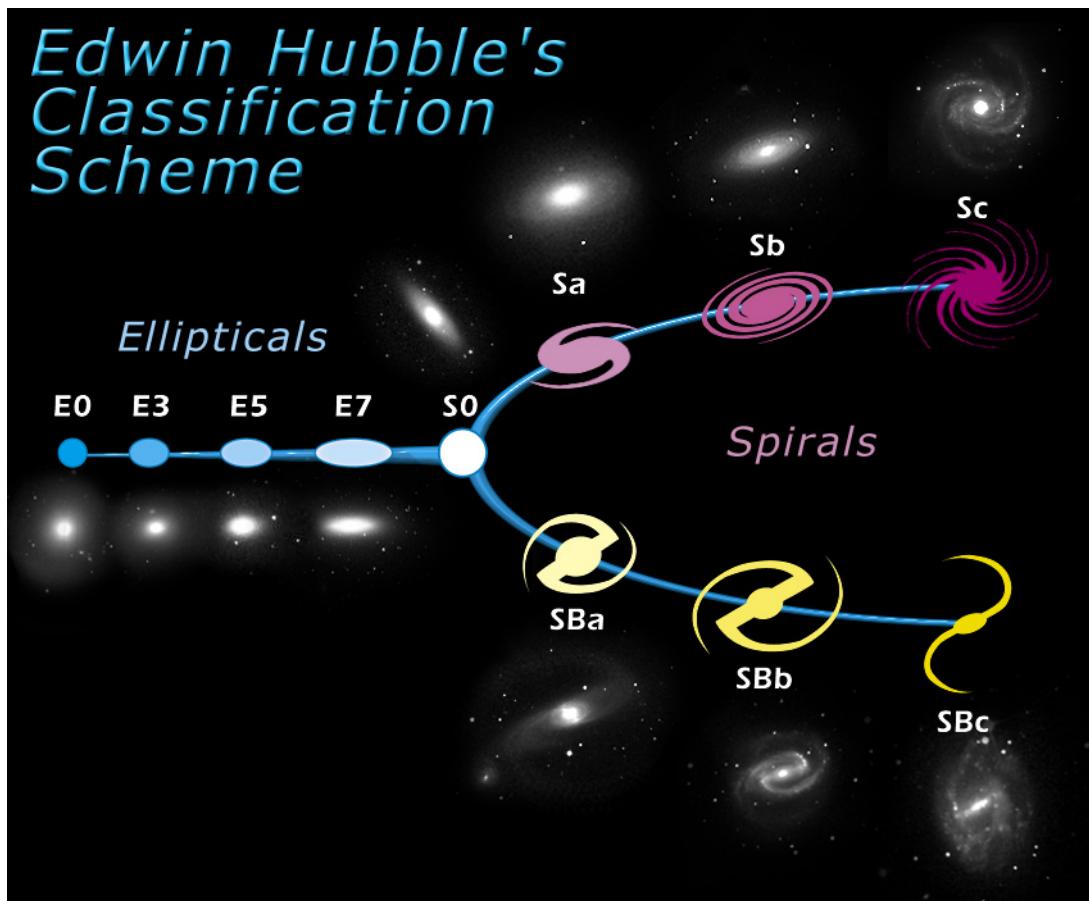


Figure 1.1: The Hubble sequence as devised by [Hubble 1926](#) and updated by [Sandage 1961](#). Image taken from information@eso.org (1999). Galaxies are ordered according to their visual complexity, progressing from elliptically (left) to lenticulars in the centre. Spiral galaxies form the right of the diagram, with barred-spirals on the bottom and non-barred, "normal", spirals at the top.

Black holes are defined as regions of spacetime so dense that nothing, not even light, can escape. A simplistic model places a singularity - a point of infinite density and zero volume - at the centre and the Schwarzschild radius to define a region around it where information cannot escape. The idea of black holes can be seen as early as [Michell 1784](#), who showed that in Newtonian physics, if a star was dense enough its escape velocity would be greater than the speed of light. Though the idea of massive, invisible stars was an exciting prospect, the interest in this waned as the wave-like properties of light were discovered and their assumed-zero mass lead scientists to be unsure if gravity could affect it.

These concepts of black holes became relevant again however, in the early 20th century,

when Einstein developed his theory of general relativity (Einstein 1916, eng. translation: Einstein et al. 1920). His field equations described gravity as a bending of space-time which could therefore impact light, and Schwarzschild quickly discovered a solution to these equations defining the Schwarzschild radius from a singularity, beyond which light could not escape (Schwarzschild 1916, eng. translation: Schwarzschild 1999). The exact nature of the resulting surface formed by the Schwarzschild radius remained a mystery until 1958, where physicist David Finkelstein described it as 'perfect unidirectional membrane' stating that influences could only pass beyond the surface in one direction, implying that particles could not escape it (Finkelstein, 1958). The actual term 'Event Horizon' used in reference to black holes was later coined in Rindler 1956.

There is a wealth of evidence for the existence for black holes including the previously mentioned observations of stars orbiting the centre of mass of a galaxy. This includes:

1. Measurements of the proper motion of stars about the galactic centre of the Milky Way was used to estimate the mass of Sagittarius A* in Ghez et al. 1998. Based on mass and radius estimates, the authors concluded that Sagittarius A* is a black hole.
2. In September 2015, the gravitational waves were detected at the Laser Interferometer Gravitational-wave Observatory. These waves matched the general relativity predicted shape for the merger and subsequent coalescence of a pair of black holes (LIGO Scientific Collaboration and Virgo Collaboration et al., 2016).
3. The X-ray binary system Cygnus X-1 is one of the brightest and well studied X-ray sources in the night sky (Webster & Murdin, 1972). Measurements of X-ray variability confirm the non-stellar source of the pair to be extremely compact and its mass has been estimated to be on the order of $10M_{\odot}$, well above the upper limit for a neutron star. From this it is widely believed that the binary pair is comprised of a black hole and a star (Herrero et al., 1995).
4. Finally, one of the most recent and compelling arguments for the existence of black holes comes from the image of the event horizon about the active galaxy Messier 87 (M87), as well as the black hole in the Milky Way, Sagittarius A* pictured in Figure 1.2 (Collaboration et al., 2019).

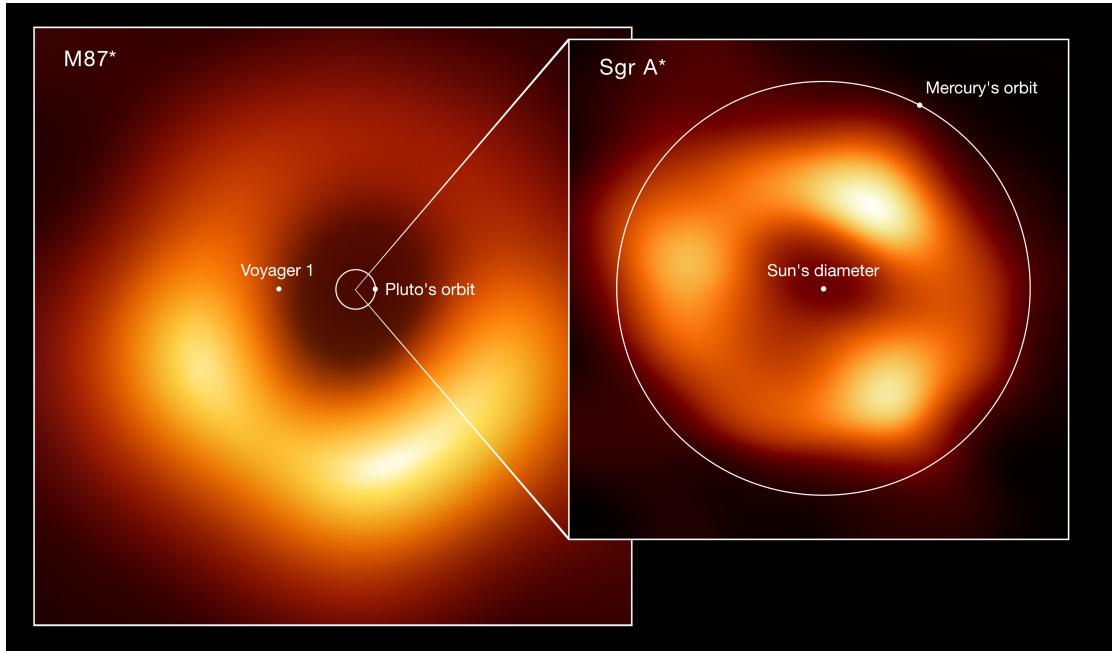


Figure 1.2: Image of the event horizon about the black hole in the galaxy Messier 87 (left) as well as the event horizon of Sagittarius A*. (right). The relative scales of the event horizons are shown in the diagram.([Collaboration et al. 2019](#); [Collaboration et al. 2022](#)).

1.2.2 Discovery of Active Galactic Nuclei

The image of the event horizon of M87’s black hole is not only significant due to it being the first image of an event horizon, but also because M87 is an active galaxy, which in of itself is a major piece of evidence for black holes.

Active galaxies are galaxies that host an active galactic nucleus (AGN). Active galaxies are extremely powerful systems, being one of the few objects to emit across the entire electromagnetic spectrum (e.g., Edelson & Malkan 1987; Collier & Peterson 2001; Cackett et al. 2021), and the central AGN engine is believed to be powered by accretion onto a super massive black hole (Salpeter 1964; Kormendy & Richstone 1995).

AGN emission has been observed as early as 1909 in Fath 1909. Here the authors aimed to test the theory that the spectra of the ‘spiral nebulae’ were truly continuous, as commonly claimed at the time. Amongst the objects observed, the spectrum of the nuclear component of NGC 1068 was taken, where it was noted that it showed both absorption and emission lines.

Later, more evidence on the unique nature of active galaxies was reported. Humason 1932 noted that the emission from the nuclear component of NGC 1275 appeared near-stellar. Finally, in his seminal paper, Seyfert 1943 measured the properties of a unique class of galaxies. He noted that, in agreement with Humason 1932, the nucleus of these galaxies appear bright and point-like, but also showed other unique properties. The six galaxies observed had very broad emission lines and the width of these emission lines increased with the luminosity of the nucleus as well as the nuclear-to-host light ratio. Other such galaxies with similar unusual properties were eventually named "Seyfert galaxies", however this research occurred during the infancy of active galaxy research in astronomy.

It was only with the discovery of high energy, radio-loud quasar astrophysics that the historical measurements of active galaxies were popularised and AGN physics became a real area of interest. In Baade & Minkowski 1954 discussion of discrete radio sources in the universe, they state that the spectrum of Cygnus A - a radio-loud galaxy - is similar to the spectrum of NGC 1275, one of the size original Seyfert galaxies. This similarity was considered tentative, however, as the Seyfert sources are not radio-loud. Finally, Schmidt 1963 identified the radio-loud active galaxy 3C 273 at redshift $z=0.158$. Immediately it is stated that this source appears as a star-like nucleus with a radio jet outflow, and that in the absence of proper motion measurements the object is extra-galactic in nature. As more of these extra-galactic 'quasi-stellar' radio sources were identified, they were given the name 'quasars' in the literature.

Over the next decades, the active galaxy theory formed, with quasars and Seyfert galaxies both being thought to contain bright nuclei, or an active galactic nucleus (AGN). Seyfert galaxies seemed to be the lower luminosity counterpart of quasars, where the AGN emission is comparable to the stellar emission of the galaxy, whereas quasar AGN emission dominated the total luminosity of the system.

1.2.3 AGN structure

Active galactic nuclei (AGN) are one of the few objects in the Universe known to emit across the entire electromagnetic spectrum. Since their discovery, uncovering the processes that drive multi-wavelength AGN emission has been a key area of study, however it is still not fully understood.

As astronomical research advanced, more detailed measurements of galaxies beyond basic morphology was collected. [Fath 1909](#) set out to determine the nature of the "spiral nebulae". In his work he measured only narrow, nuclear spectra of many objects, and found that whilst many can be explained as the superposition of stars of various spectral types and different surrounding gasses causing absorption lines, in the case of NGC 1068, the object was reported to have a composite spectrum showing both emission and absorption lines on a continuous background.

Active galaxies refers to a sub-type of galaxy that hosts an active galactic nucleus (AGN). AGN appear as extremely bright points in the centre of a galaxy when comparing an active galaxy to an inactive counterpart and this additional emission is thought to occur due to accretion of material onto the central SMBH.

[Seyfert \(1943\)](#) then revived this relatively obscure result when his measurements of six galaxies, including NGC 1068, found similar very broad emission lines in the galaxies. He noted that the width of these lines increased with nuclear to total light ratio of the galaxy as well as the fact that the broadening of these lines did not occur in other galaxies. Finally he notes that all of these galaxies have nuclei that appear bright and point-like, being "scarcely distinguishable from stars", which is in agreement with the paper on NGC 1275, one of the studied galaxies that [Humason 1932](#) also studied some years earlier.

The Unified Model of AGN presents the most widely accepted description of how AGN emission occurs. First presented by [Antonucci 1993](#), the Unified Model assumes that the basic underlying structure of AGN emission is the same regardless of the type of AGN observed, with differences in properties being attributed to different viewing angles between the AGN and the observer.

1.2.4 Variability

Active Galactic Nuclei (AGN) have long been observed within the Universe ([Seyfert, 1943](#)) and are characterised by their dynamic multi-wavelength emission that spans the entire electromagnetic spectrum (e.g., [Edelson & Malkan 1987](#); [Collier & Peterson 2001](#); [Cackett et al. 2021](#)). This AGN emission, which can often outshine the entire stellar output of the host galaxy, is believed to arise from accretion of material onto a

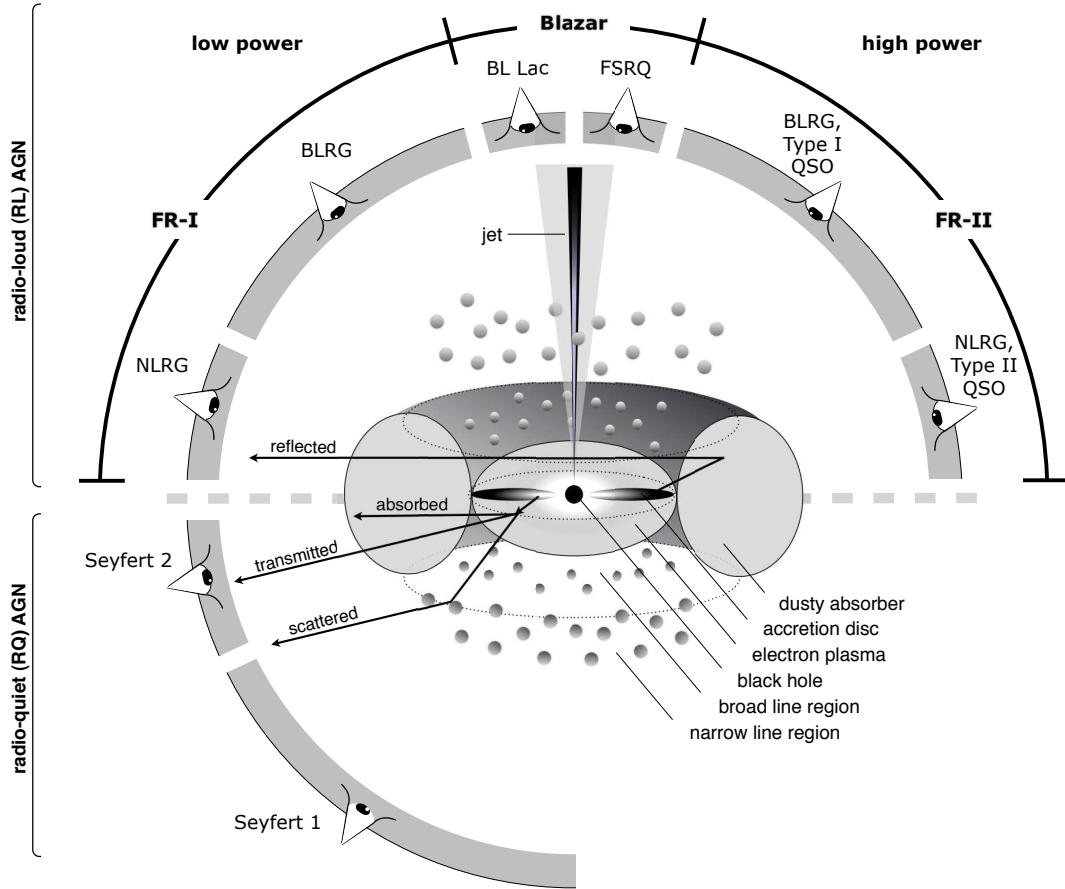


Figure 1.3: Beckmann & Shrader (2013)

central supermassive black hole (Salpeter 1964; Kormendy & Richstone 1995). AGN emission is invoked across many aspects of galaxy evolution to help explain observed phenomena, but this activity, and the underlying mechanisms that drive it, is still not fully understood.

Due to the small physical size of the AGN's central engine, accretion and emission from AGN occurs on scales many orders of magnitude smaller than that of the host galaxy. Consequently, resolving the central nucleus is simply not feasible for galaxies outside our local neighbourhood (e.g., Padovani et al. 2017). The difficulty in unpicking AGN emission from that of its host galaxy also poses a significant barrier in understanding the structures present within an AGN, and the impacts of the accretion process on the surrounding region (Grogin et al. 2005; Gabor et al. 2009; Pierce et al. 2010; Fan et al. 2014). As a result, despite many theories within the literature, there is no firm

consensus on the potential trigger (or triggers) that activates an AGN. Furthermore, we are currently unable to observe any given galaxy and know with certainty how and why it is, has been, or will become, active in its lifetime. In order to determine robust answers for these questions, a complete census of active galaxies in the Universe is necessary to allow for the study of the cosmic evolution of AGN.

Due to the nature of the accretion process, AGN emission is not static, but varies in flux over time at every wavelength it has been observed (e.g., Fitch et al. 1967, Sánchez et al. 2017). It has been hypothesised that much of this variability is caused by stochastic processes in the accretion disc, and as such allows for the study of AGN on the relatively tiny scales they span compared to the size of a galaxy. Variability timescales have also been found to increase with wavelength. For example, emission at higher frequencies, such as X-rays, vary within hours, while UV and optical variations take days to weeks. The longer wavelengths, such as infrared (IR), typically vary on timescales of months or years (e.g., Berk et al. 2004). AGN emission theory couples the wavelengths of emission to structures within the AGN itself, with longer wavelengths being generated at larger distances from the core. For example, X-rays are believed to be generated in the X-ray corona, UV and optical emission in the accretion disk, and IR emission originating in a surrounding dusty torus (e.g., Bianchi et al. 2022).

1.3 Thesis Structure

All magnitudes stated are AB magnitudes. We use a Λ cold dark matter (Λ CDM) cosmology, with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$.

Chapter 2

Data

In this work, we make use of data from multiple deep surveys: the UKIDSS Ultra Deep Survey (UDS; Almaini et al., in prep); combined with the *Chandra* Legacy Survey of the UDS field (X-UDS; [Kocevski et al. 2018](#)). A plot of the extent of the fields is shown in Figure 2.1.

2.1 UDS

The UDS is the deepest of the UKIDSS surveys ([Lawrence et al., 2007](#)) and the deepest NIR survey over $\sim 1 \text{ deg}^2$. Its *JHK* band imaging was taken over an 8 year period from 2005–2013 using the WFCAM instrument at UKIRT ([Casali et al., 2007](#)). Although not primarily designed to study variability, the collection of the data spread over eight years offers a powerful resource for long-term infrared variability studies. In addition to this, the field is well studied and as such has additional imaging in many other wavebands including:

- u' -band imaging from the Canada–France–Hawaii Telescope (CFHT) MegaCam.
- B , V , R , i' and z' -band optical imaging from the Subaru *XMM-Newton* Deep Survey (SXDS; [Furusawa et al., 2008](#)).
- Y -band imaging from the VISTA VIDEO survey ([Jarvis et al., 2013](#)).

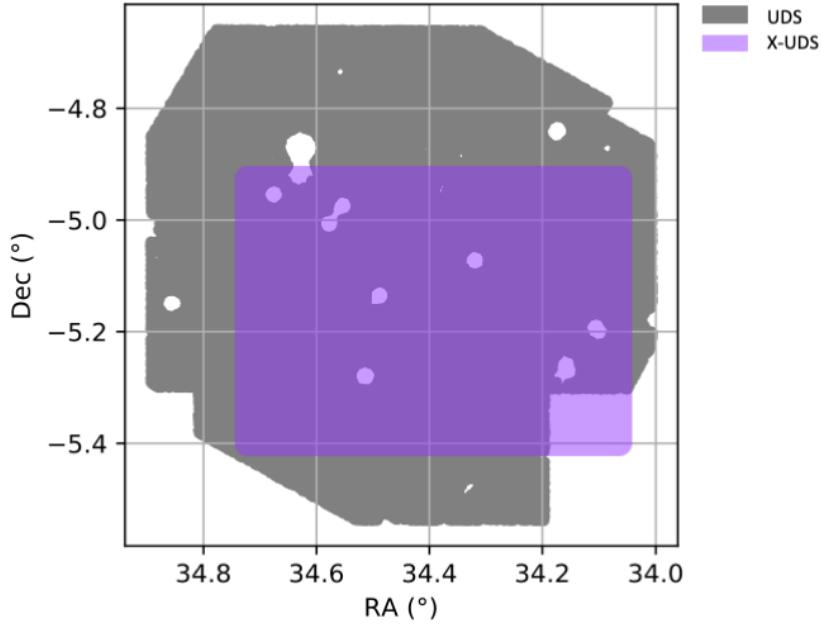


Figure 2.1: The survey region of the Ultra Deep Survey (UDS) and the *Chandra* Legacy Survey of the UDS field (X-UDS). The grey shaded area shows the subset of the ground-based UDS field where there is reliable photometry in all 12 photometric bands, and the purple shaded area shows the coverage from the *Chandra* X-UDS imaging.

- $3.6\mu\text{m}$ and $4.4\mu\text{m}$ mid-infrared (MIR) IRAC imaging from the *Spitzer* UDS Legacy Programme (PI: Dunlop).

The DR11 is the latest data release from the Ultra Deep Survey (UDS). This data release has 296,007 K -band detected sources and 5σ limiting depths of $J = 25.6$, $H = 24.8$ and $K = 25.3$ (AB in 2-arcsec diameter apertures; Almaini et al. 2017; Almaini et al., in prep.). From this data release we make use of the ‘*best galaxies*’ subset which covers 0.62 deg^2 , and comprises objects identified in unmasked regions of the field with reliable photometry in all 12 bands, the deepest IRAC imaging, and with galactic stars removed. Masked regions correspond to boundaries of the science image, artefacts, bright stars and detector cross-talk. The *best galaxies* subset contains 202,282 K -band detections.

2.1.1 Redshifts

Of the 202,282 galaxies, 6558 have secure spectroscopic redshifts provided by complementary spectroscopic surveys (e.g., UDSz, VANDELS; Bradshaw et al., 2013; McLure

et al., 2013; Maltby et al., 2016; McLure et al., 2018; Pentericci et al., 2018). For non-variable objects, spectroscopic redshifts are used (where available); otherwise, photometric redshifts are adopted.

Photometric redshifts for non-variable objects were calculated according to the methodology described in Simpson et al. (2013). For this, the 12-band photometry was fit using a grid of galaxy templates constructed from the stellar population synthesis models of Bruzual & Charlot (2003), and used the publicly available code `EAZY` (Brammer et al., 2008). These photometric redshifts have a typical accuracy of $\frac{\Delta z}{(1+z)} \approx 0.018$. Additional properties used in this work (e.g. stellar mass and luminosity; Almaini et al., in prep), are based on these redshifts and are entirely adequate for our purposes.

In this paper, we identify IR-variable objects (see Section 3.1). For these objects, spectroscopic redshifts were used (where possible) over photometric determinations. For the variability detected sources for which spectroscopic redshifts were not available, inaccuracies in the photometric redshifts are a potential concern due to the AGN emission not being accounted for. To address this, we have recalculated the photometric redshifts for these objects via the `EAZY` redshift fitting code. Here additional reddened and unreddened AGN templates were included in the fitting. Comparing the median absolute deviation of $\frac{\Delta z}{(1+z)}$ before and after including the recalculated photometric redshifts, indicates the redshifts improve only marginally from $\sigma_{\text{MAD}} = 0.10$ to $\sigma_{\text{MAD}} = 0.098$. This demonstrates the initial photometric redshift values to be largely robust. Regardless, the recalculated redshifts for the IR-variable active galaxies are used throughout this work, though we note that using the original photometric redshifts made no significant difference to our analysis or conclusions.

2.1.2 Stellar Masses

Stellar masses (Almaini et al., in prep), were calculated using the method described in Simpson et al. (2013). Here, the 12-band photometry was fit to a grid of synthetic SEDs from the stellar population models of Bruzual & Charlot (2003) with a Chabrier (2003) initial mass function. Typical uncertainties in these stellar masses are of the order ± 0.1 dex. The redshift-dependent, 90 per cent stellar mass completeness limits were calculated using the method described in Pozzetti et al. (2010). A second order polynomial was fit to the resulting completeness limits across a wide redshift range to

give a 90 per cent mass completeness curve of the form $\log_{10}(M_*/\text{M}_\odot) = -0.04z^2 + 0.67z + 8.13$.

2.2 X-UDS

The X-UDS survey is a deep X-ray survey of a sub-region of the UDS field carried out by the *Chandra* X-ray Observatory's Advanced CCD Imaging Spectrometer (ACIS). It comprises a mosaic of 25 observations of 50 ks exposure, totalling 1.25 Ms of imaging. It covers 0.33 deg^2 in total (Kocevski et al., 2018) and has a flux limit of $4.4 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the full band (0.5–10 keV). In total, 868 point sources were identified.

This data set was matched to the UDS DR11 *K*-band catalogue using the methodology described in Civano et al. (2012), which adopted the maximum likelihood method described in Sutherland & Saunders (1992). Through this analysis, we find that 710 of these point sources are associated with *K*-band-selected galaxies in the UDS DR11.

Chapter 3

Quantifying AGN variability

3.1 Selecting AGN based on their IR variability

IR-variable AGN are selected from the UDS DR11 using the technique first developed and used in [Elmer et al. \(2020\)](#). Here, the authors were able to construct NIR light curves from multiple flux measurements that spanned 7 semesters in the K -band. Errors on the flux measurements were self-calibrated, based on the population variance in flux of the non-variable objects, as this provided a better fit to the data than the errors generated by SExtractor (see Figure 3. in [Elmer et al. 2020](#)). To do this, the authors began by convolving each semester stack of images with a Gaussian kernel to match the stack with the poorest quality PSF. This ensured that the differences in flux measurements were due to intrinsic AGN variability and not changes in the point spread function from semester to semester. A preliminary χ^2 analysis was then performed to remove the most variable sources and the remaining light curves were normalised and split into bins based on flux, epoch and quadrant. From this the standard deviation of the binned flux values provided the photometric error on the measurements for the objects in that bin.

After the publication of [Elmer et al. 2020](#), additional J -band imaging was incorporated into the dataset. First an updated catalogue of galactic stars was developed for the UDS DR11 release, none of which were included in the initial K -band sample selection. These stars were used to improve the PSF images prior to convolving the data to match the semester with the poorest PSF (see Section 2.2 of [Elmer et al. 2020](#)), allowing for an improved sample selection in the K -band. Furthermore, the 2006B semester in the J -band had sufficient observations to allow it to be included in the light curves. This gives the J -band a total of 8 epochs for study.

We further select only objects with reliable (unmasked) photometry in all 12 bands, to ensure the most reliable photometric redshifts. Objects identified as galactic stars were excluded, as were any galaxies close to cross-talk detector artefacts. We also exclude any objects with formally negative flux values in any individual semester, as described in [Elmer et al. \(2020\)](#). This final step largely excluded very faint galaxies at $K > 25$, close to or beyond the formal detection limit of the survey. Inspecting this faint subgroup reveals that all would be excluded by the eventual J -band magnitude cut described in Section 3.4, so have no impact on our analysis. Overall, these rejection criteria yield a final sample of 114,243 light curves for this study.

Errors on the flux measurements were self-calibrated, based on the population variance

in flux of the non-variable objects at the same apparent magnitude, as this provided a better fit to the data than the errors generated by SExtractor (see Figure 3 in Elmer et al. 2020). A full description of this process can be found in Section 2.2 of Elmer et al. (2020).

IR-variable AGN were selected using a χ^2 analysis applied to the IR light curves based on the null hypothesis that flux measured from the object is constant with time. Thus we calculate

$$\chi^2 = \sum_i \frac{(F_i - \bar{F})^2}{\sigma_i^2}, \quad (3.1)$$

where for each semester i , F_i is the flux of an object, σ_i is the corresponding uncertainty and \bar{F} is the mean flux of that object across all imaging epochs. A threshold of $\chi^2 > 30$ was used for the K -band and we use $\chi^2 > 32.08$ for the J -band. The differing χ^2 limits give the same p-value for both χ^2 distributions based on the J and K -band light curves, accounting for the different number of imaging epochs and therefore differing degrees of freedom. If a galaxy satisfies either or both conditions, it is classed as hosting a variable AGN.

Utilising this method to select significantly variable objects via the χ^2 analysis, we are able to identify a sample of 705 candidate active galaxies for study (430 from K -band variability, 471 from J -band variability, with 196 detected by both). We recover all of the 393 K -band selected AGN found in Elmer et al. 2020, with a modest increase due to the improvements in the data analysis since the publication of that work. From the initial data set of 114,243 galaxies with IR light curves, we would expect a total of 4 false positives based on a χ^2 distribution with this number of degrees of freedom.

To search for potential supernovae in the sample, tests were carried out according to Section 5 of Elmer et al. 2020. We identified 36 of the 471 J -band variables (7.6 per cent) for which the variability is largely driven by one epoch. Inspection of both the J and K -band imaging and comparing epochs revealed no obvious signs of supernovae (e.g., off-nuclear sources). No additional supernova candidates were identified among the new K -band variables not analysed by Elmer et al. 2020. Removing this small number of galaxies had no influence on any of the key conclusions presented in this work.

3.2 Galaxies on the edge of the science image

Visual inspection revealed a suspicious sample of 104 variable objects located very close to the detector edges. These objects were inspected individually within each epoch, and approximately ~ 33 per cent were identified as potentially fake variables. All objects were found to be real galaxies, but in many cases false variability could be attributed to problems with background subtraction at the detector edges. As such, we re-ran all analysis both with and without this sub-sample of galaxies, and found no significant change in the overall reported trends. Therefore, we removed these edge objects entirely from the analysis to ensure robust results. The remaining sample consists of 601 galaxies.

We note that the pattern of false variables occurred only at the outer edges of the UDS imaging. There was no evidence for false positives close to the internal WFCAM chip boundaries in the UDS mosaic.

3.3 Measuring real variability: maximum likelihood

For any measurement of an active galaxy light curve, we know that the observed dispersion in flux (σ_{obs}) is due to a combination of the intrinsic magnitude variations due to the active galactic nucleus (σ_Q) and the measurement noise (σ_{noise}) such that

$$\sigma_{\text{obs}}^2 = \sigma_Q^2 + \sigma_{\text{noise}}^2. \quad (3.2)$$

Consequently, if we are to measure the properties of the AGN, we have to be able to separate out these two effects.

As such, to calculate the fractional variability amplitude due to AGN emission (σ_Q), we make use of a maximum likelihood technique. This method, developed in Almaini et al. (2000), allows for an estimate of the noise-subtracted intrinsic fractional variance (σ_Q) of the AGN, within the observed variability (σ_{obs}). We first take any given AGN light curve and generate a likelihood function

$$L(\sigma_Q | x_i, \sigma_i) = \prod_{i=1}^N \frac{\exp[-(x_i - \bar{x})^2 / 2(\sigma_i^2 + \sigma_Q^2)]}{(2\pi)^{1/2}(\sigma_i^2 + \sigma_Q^2)^{1/2}}. \quad (3.3)$$

To generate each point in the likelihood curve, we normalise each galaxy light curve such that the average flux (\bar{x}) is unity. We then step through possible values of fractional AGN variability (σ_Q) using the measurement of the flux in each semester (x_i) and its corresponding measurement error (σ_i). To get the final likelihood measurement, we take the product of the N values that have been calculated where N is the number of flux measurements in a given light curve.

In order to determine the most likely value of σ_Q for each active galaxy, we simply select the value of σ_Q that maximises the likelihood function, as seen in Figure 3.1. Here the 1σ errors are calculated by assuming the likelihood curve has a Gaussian shape.

3.4 Variability detection limit

The χ^2 detection method is inevitably sensitive to photometric errors, and thus in fainter galaxies we can only expect to detect variability at higher fractional amplitude. We can attempt to quantify this effect, to estimate our completeness in identifying variable AGN with a range of intrinsic variability amplitudes (σ_Q), and over a range of apparent magnitudes. To begin, we remove any active galaxies via their IR variability or X-ray emission from the initial sample of 114,243 galaxies and then split the remaining inactive galaxies into bins based on apparent magnitude. Then, to simulate variability in the inactive galaxies, we artificially introduce variability to their light curves assuming a Gaussian distribution of variations. We require this (variable) component to have a mean of zero and a standard deviation equal to the degree of variability we are simulating, and add this distribution to the normalised inactive galaxies light curves. We then re-run the χ^2 and maximum likelihood analysis on the ‘new’ light curve for each galaxy, which now contains simulated variability. This allows us to determine if it is now classed as hosting a significantly variable object by the χ^2 analysis and to ascertain the most likely amplitude of simulated variability using the maximum likelihood technique. This procedure is repeated for a range of variability amplitudes and for each apparent magnitude bin. The results are then used to determine, for a given apparent magnitude, the minimum fractional variability amplitude required for an AGN to be consistently detectable. This also allows us to compare the known simulated variability amplitude

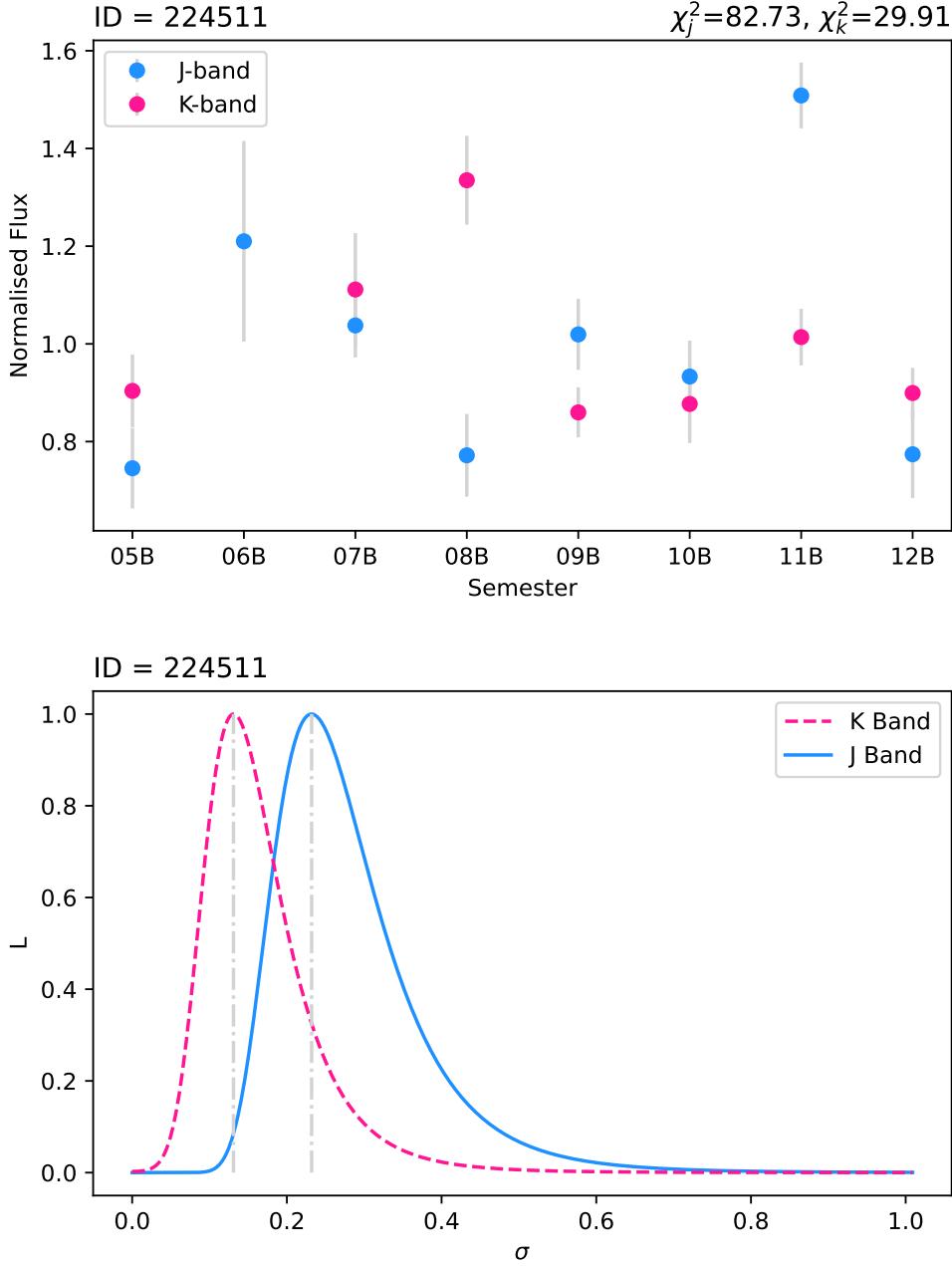


Figure 3.1: Example light curves for a variable galaxy candidate in both the J and K -band (top panel) and the corresponding normalised likelihood curves (bottom panel). The threshold for recovery of AGN variability from a given light curve is $\chi_K^2 > 30$ and $\chi_J^2 > 32.08$. As shown by the grey lines in the bottom panel, the variability amplitude is determined by selecting the corresponding value for σ_Q that maximises the likelihood function. This galaxy is only classified as formally variable in the J -band (blue), as shown by the value of the χ^2 .

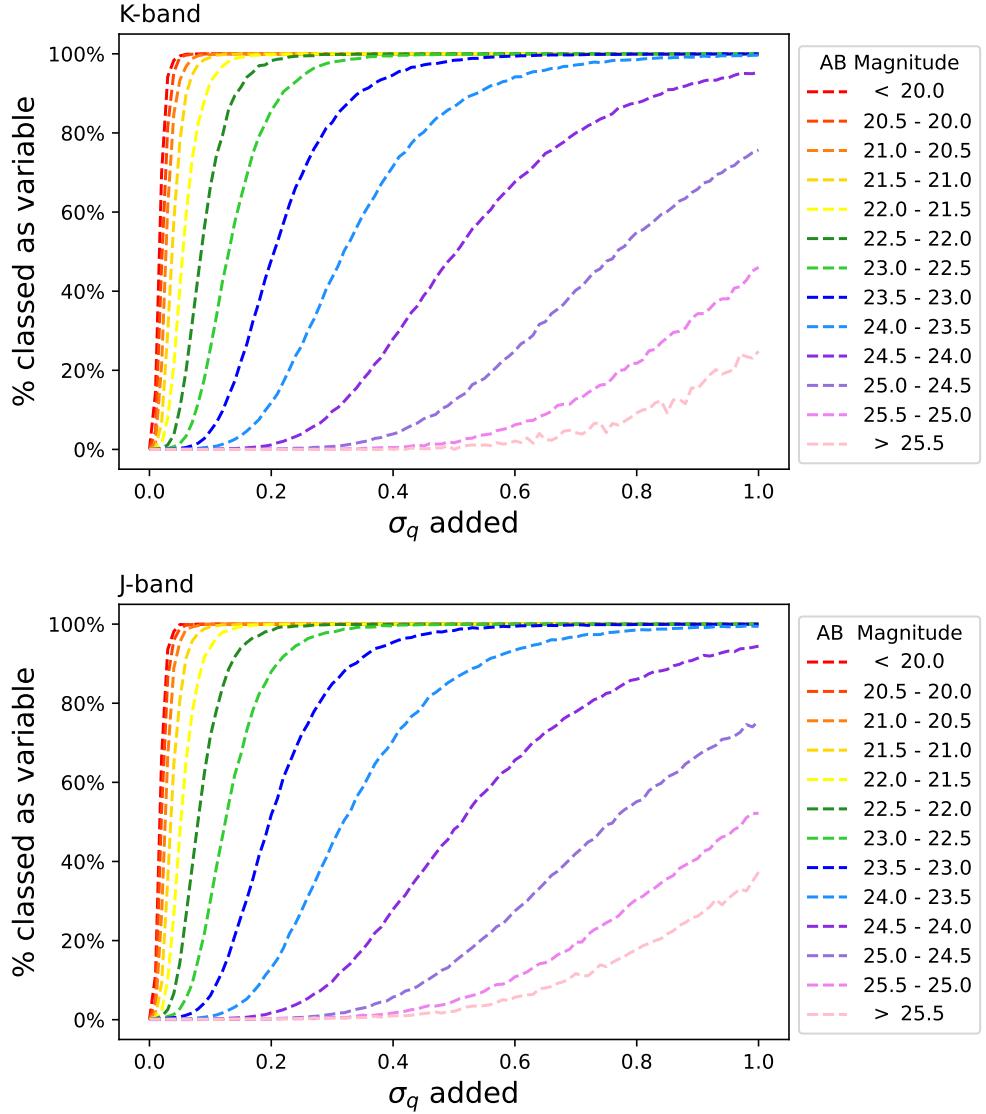


Figure 3.2: The fraction of galaxies classed as hosting variable AGN compared to the level of artificial variability added to the inactive galaxy light curves. Results are shown for the *K*-band (top panel) and *J*-band (bottom panel). Each dashed line represents a different apparent magnitude bin. In the brightest bins, lower uncertainties on measurements allow for low amplitudes of variability to be recovered. However, larger variability amplitudes are required for AGN to be detected in the faintest galaxies.

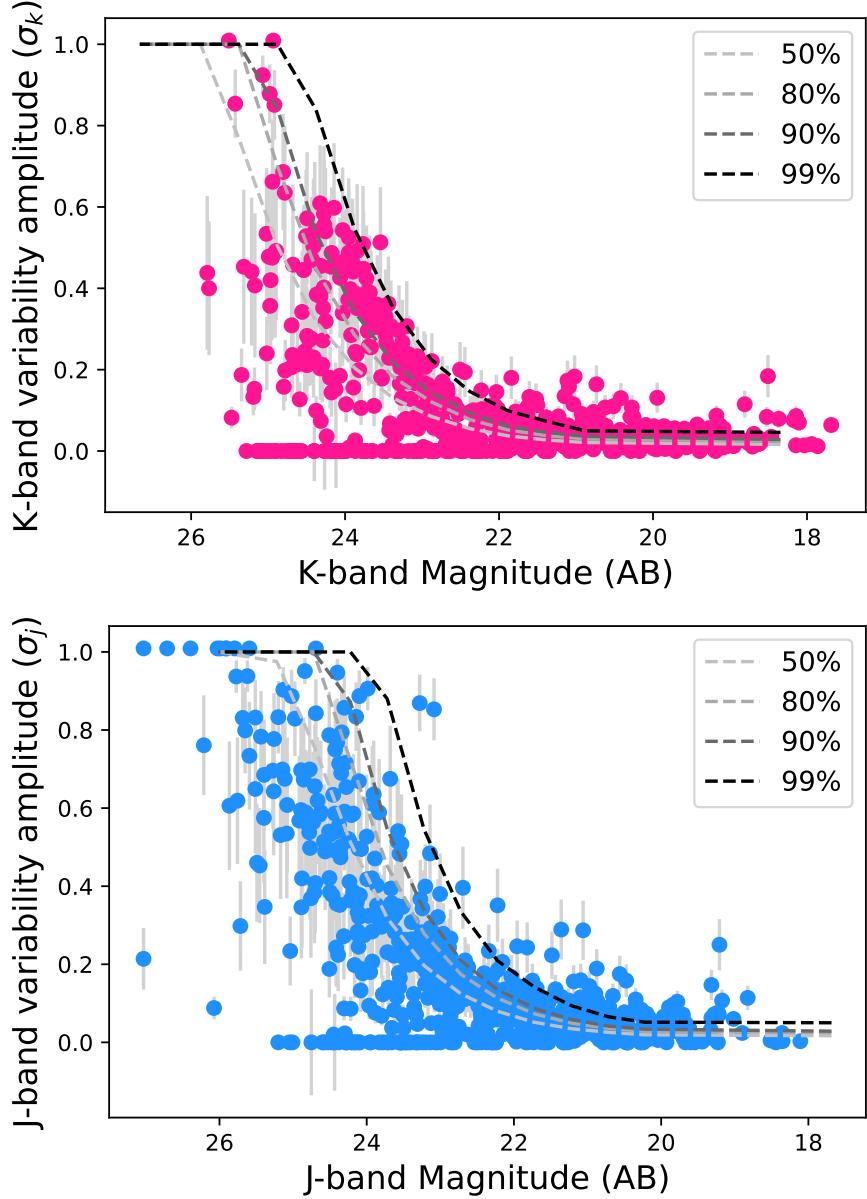


Figure 3.3: AB magnitude vs. variability amplitude for the *real* variable active galaxies. Pink points indicate galaxies selected as hosting variable AGN in the K -band (top panel), while blue points show the same data but for the J -band (bottom panel). Grey 1σ errors are based on assuming a Gaussian fit to the likelihood curves. Overlaid are detection limit curves for different levels of completeness. We use the 90 per cent curve as this threshold provides a high level of completeness without over-reducing the sample size.

to the amplitude recovered via the maximum likelihood method.

We find that the maximum likelihood technique accurately recovers the amplitude of input AGN variability. Sampling galaxies from each magnitude bin, the average difference in variability amplitude is consistently of the order of 1 per cent. Using these simulations, we are also able to calculate the fraction of galaxies classed as hosting an AGN for every value of simulated σ_Q in each magnitude bin (see Figure 3.2). This provides a suitable estimate for the completeness of our NIR variables, as a function of both apparent magnitude and variability amplitude.

As seen in Figure 3.3, for a given value of an AGN’s fractional variability amplitude and a selected completeness level, we can determine the apparent magnitude required for that selected variability amplitude to be consistently detected to the desired completeness. Throughout this work, we adopt the 90 per cent completeness threshold for a variability amplitude of 20 per cent or higher. From the J -band curve in Figure 3.3, we find this requires our galaxies to have apparent magnitudes of $m_J \leq 22.66$. In the K -band, the same limit requires an apparent magnitude of $m_K \leq 23.25$. We use the J -band limit in this work as it is stricter, and removes all galaxies excluded by the K -band limit.

3.5 Modified monthly variability amplitude

We can also probe variability on different timescales, and this allows us insight into the NIR power spectrum of the variability in the active galaxies. In addition to the semester timescale measurements of fractional variability amplitude, we calculate a modified monthly variability amplitude measurement. To do this, we modify the light curves taken on month timescales such that semester contributions to the observed variability is removed, with an example of this process being shown in Figure 3.4.

To begin, we use the infrared light-curves built in [Elmer et al. 2021](#), where flux measurements were taken between September 2005 and November 2012 on month timescales. Light curves with negative values are removed from the sample. We then group the flux measurements based on the date they were taken, with flux measurements taken within 120 days of each other grouped together. Each group is then normalised such that the average flux is unity. Finally, the maximum likelihood measurement as described in Section 3.3 is applied to the modified light curve to calculate the modified fractional

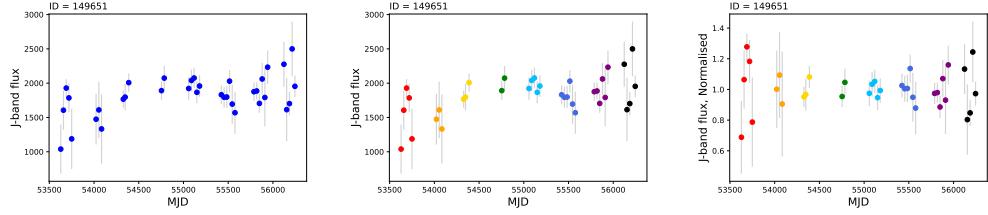


Figure 3.4: Example of the month light curve modification process in the J -band. In all plots, circular points denote flux measurements and grey lines are errorbars. Left is the measured light curve comprised of flux measurements on month timescales, centre is the group selection, where measurements within 120 day of each other are grouped together and right is the final modified light curve, where each group is normalised such that the mean is unity. The process for K -band modification is identical, with K -band data being used in place of J -band measurements.

variability amplitude on month timescales.

Chapter 4

Long-term near-infrared variability

In this work we compare the properties of the 601 NIR variability selected active galaxies in Chapter 3 to a sample of 710 X-ray detected active galaxies from the X-UDS (Chapter 2). We then investigate if and how the properties of active galaxies differ depending on the detection method. This work was published in Paper I.

4.1 Introduction

Variability has been shown to be a useful tool in selecting AGN, being able to complement other selection methods by succeeding where they fail. X-ray emission, for example, is commonly thought to have a high probability of selecting the most complete sample of active galaxies (e.g., [Suh et al. 2019](#), [Pouliasis et al. 2019](#)), but this method is intrinsically biased against X-ray-faint objects. In [Trevese et al. \(2008\)](#), a study of low-luminosity AGN found that only 44 per cent of their optical-variability-selected active galaxies have associated X-ray emission. [Pouliasis et al. \(2019\)](#) also selected AGN via optical variability and X-ray emission, but additionally employed the use of IR colour selection. They find that 23 per cent of their variable sample have associated X-ray emission, and only 12 per cent of their variable sample satisfies the IR colour selection criteria for the presence of an AGN. More recently, [Lyu et al. \(2022\)](#) used a wide combination of selection techniques, including radio emission, X-ray detection, variability, UV–IR SED analysis, optical spectroscopy, and IR colour selection in an attempt to find a complete sample of active galaxies in the GOODS-S field. They concluded that no single method was able to select a complete sample of galaxies, and the overlap in the AGN found by different techniques was small.

AGN variability is a relatively unexplored property at infrared wavelengths due to the time required to observe it, but one which is believed to provide significant insight into the nature of the outer edges of the AGN system. In principle, this technique may also provide an advantage in identifying heavily-obsured and/or high-redshift AGN, which may be missed by optical/UV selection techniques. Furthermore, deep wide-field imaging can allow us to study thousands of galaxies simultaneously.

Until recently, studies of IR variability either focused on a handful of individual objects ([Cutri et al. 1985](#), [Lira et al. 2011](#), [Lira et al. 2015](#)), observed AGN selected by other means ([Kouzuma & Yamaoka 2012](#), [Sánchez et al. 2017](#), [Son et al. 2022](#)), or studied

light curves that are not well sampled (Edelson & Malkan, 1987) or constructed from observations from multiple different surveys (Neugebauer et al., 1989). However, Elmer et al. (2020) were the first to select AGN in large numbers based purely on their NIR variability using a single deep data set, and it is this sample we build upon in this work.

In this paper, we investigate the properties of active galaxies selected using NIR variability. We use J -band light curves to select significantly variable AGN in addition to the K -band light curves and method described in Elmer et al. 2020. We then compare the properties of these galaxies to a sample of AGN selected via X-ray selection, to determine if and how the properties of active galaxies differ depending on the detection method. We make use of nearly a decade of IR observations provided by the Ultra Deep Survey (UDS; Almaini et al., in prep); the deepest component of the UKIRT (United Kingdom Infra-red Telescope) Infrared Deep Sky Survey (UKIDSS; Lawrence et al., 2007). We use this data to select 601 active galaxies between $0 < z \leq 5$ based purely on their IR variability using the technique developed, as well as the data constructed, in Elmer et al. (2020). We then compare the properties of these active galaxies to those found using X-ray emission from the X-UDS survey (Kocevski et al., 2018), as well as a control sample of inactive galaxies.

4.2 X-ray faint active galaxy populations

We applied the AGN variability detection method described in Section 3 to the UDS DR11, and compared the results to the full-band (0.5–10 keV) *Chandra* X-UDS catalogue described in Section 2.2. If we limit the UDS and the X-UDS to the same survey area (see Figure 2.1, for reference), the samples are largely separate. Of the 601 variability detected active galaxies, 292 lie within the *Chandra* imaging region. The percentage of these that are dual-detected AGN (i.e. X-ray detected and variable in the NIR) is only \sim 37 per cent (107 / 292). This represents \sim 15 per cent of the X-ray detected sample (107 / 710).

One possible explanation for this result is that NIR-variable AGN have X-ray emission that is too faint to be detected at the depth of the X-UDS survey. X-ray emission from AGN has long been known to correlate with optical/UV emission (e.g., Tananbaum et al. 1979, Avni & Tananbaum 1986). Therefore, to address this issue, we compare

the observed X-ray-to-optical luminosity ratios to determine if the variability-detected AGN are unusually X-ray quiet (for galaxies that reside within the X-UDS survey region). In Figure 4.1, we compare the monochromatic luminosities at 2 keV and 2500 Å, compared with the expected ratios assuming point-to-point spectral slopes with $\alpha_{ox} = 1$ and $\alpha_{ox} = 2$, corresponding to the typical range observed for quasars (e.g., Steffen et al. 2006).

We note, however, that in our work we make no corrections for host galaxy contributions, dust reddening, or X-ray absorption. We are comparing the observed X-ray to optical ratios, to determine if the objects selected by variability show similar ratios to those selected with deep Chandra observations.

Here, monochromatic luminosities at 2500 Å are derived from the observed optical/UV SEDs, given the source redshift, interpolating the flux between the nearest observed wavebands. The monochromatic X-ray luminosities are determined from the 0.5-10 keV X-ray flux, assuming an X-ray photon index $\Gamma = 1.9$ for all sources, as used in Elmer et al. (2020). X-ray upper limits from Kocevski et al. (2018) are used for X-ray non-detections. Overall we find that many variable active galaxies have similar optical luminosities to X-ray bright active galaxies, but the majority have only upper limits in our X-ray imaging. Based on the data available to us, the variable AGN appear systematically fainter in the X-rays.

One possible explanation is that the variable AGN are more obscured in the X-ray waveband, but deeper X-ray data will be needed to test that hypothesis. Overall, the implication is that near-infrared variability appears to detect a set of active galaxies that are largely missed by X-ray surveys at these depths.

4.3 Active Galaxy Properties

4.3.1 Stellar mass distributions and quasar contamination

In addition to there being limited overlap in AGN selected using NIR variability and X-ray detection, we find a difference in the stellar mass ranges of active galaxies selected via X-ray detection and NIR variability. Examining the mass distribution with redshift

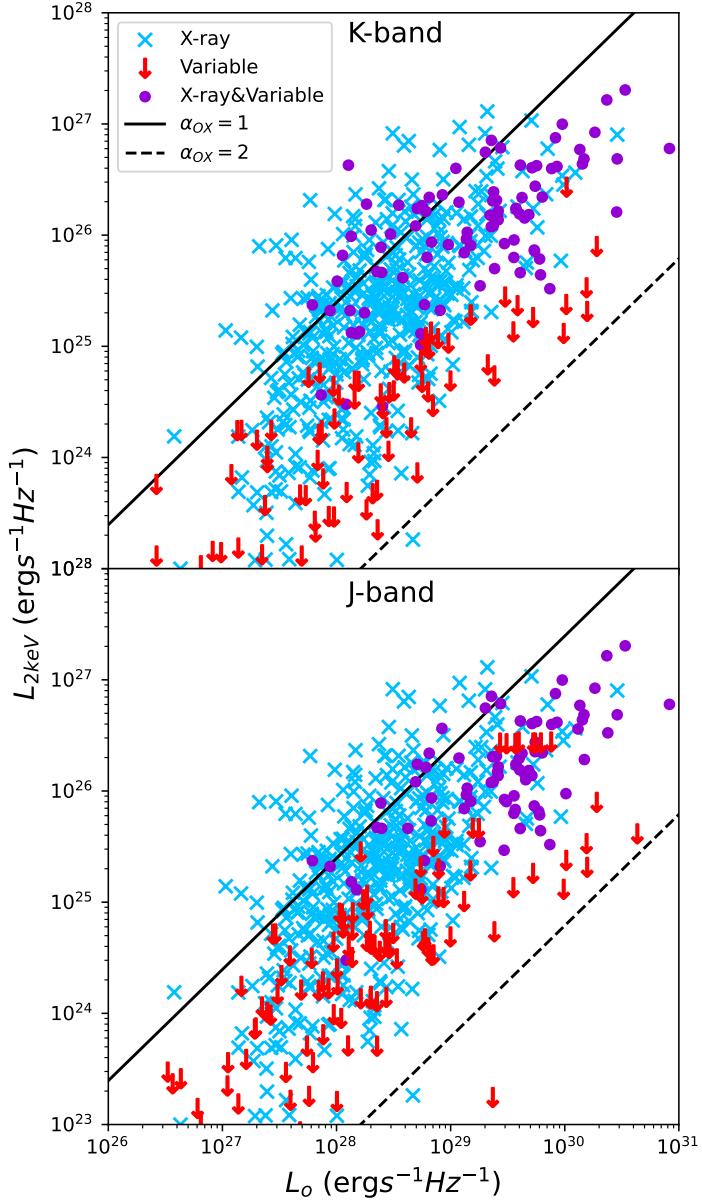


Figure 4.1: Monochromatic 2 keV X-ray luminosity vs. rest-frame optical luminosity at 2500 Å for objects imaged within the *Chandra* region of the UDS field. X-ray bright active galaxies are denoted by blue crosses and AGN detected by both NIR variability and X-ray emission are highlighted as purple dots. Upper limits are used for variability-detected active galaxies without X-ray detections, and are shown by red arrows. The top plot shows *K*-band detected active galaxies and the bottom plot shows *J*-band detected active galaxies. Black lines indicate the slopes corresponding to a spectral index (α_{ox}) of $\alpha_{ox}=1$ (solid) and $\alpha_{ox}=2$ (dashed), where α_{ox} is the spectral index between the optical and the X-ray.

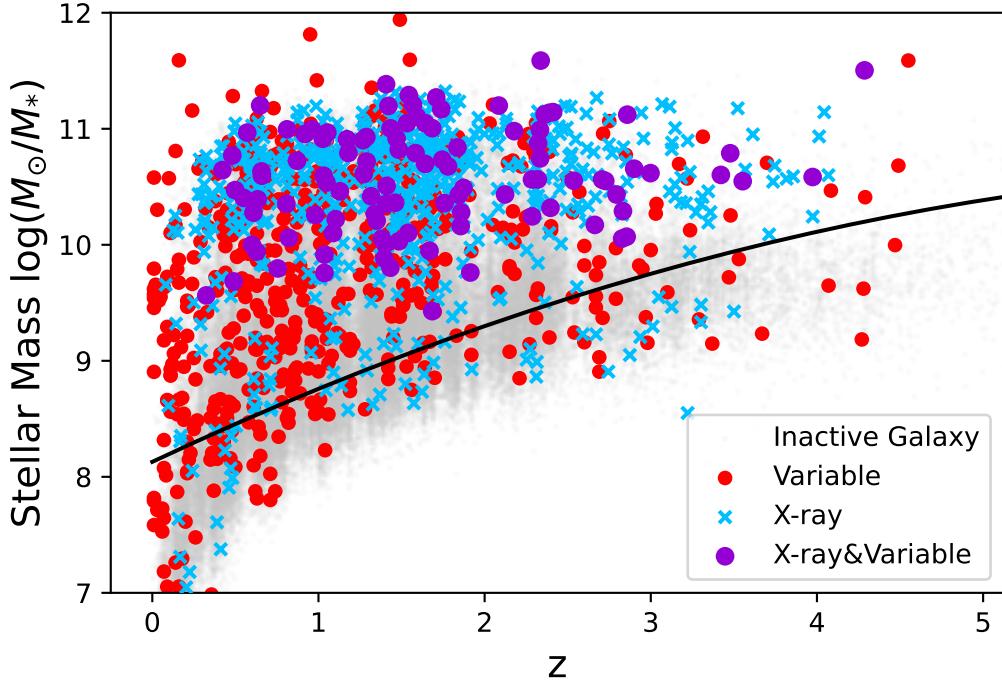


Figure 4.2: Stellar mass vs. redshift distribution for the galaxies in this study. X-ray bright active galaxies are shown as blue crosses, red circles denote variability-detected active galaxies, and purple circles show dual-detected active galaxies. Grey points are inactive galaxies, and the black curve shows the 90 per cent stellar mass completeness limit as a function of redshift.

in Figure 4.2, X-ray emission probes AGN in high-mass galaxies across all redshifts considered, with a majority of X-ray selected active galaxies having stellar masses $\geq 10^{10} M_{\odot}$. This is in contrast to the active galaxies selected through variability, which show no obvious bias towards high-mass galaxies.

To illustrate these differences, in Figure 4.3 we plot the distribution of the stellar mass of the active galaxies, separated by detection method.

We find a clear distinction between any X-ray detected AGN, which are much more likely to exist in high-mass galaxies, and NIR variability detected AGN, which show a much more extended mass distribution.

One caveat to these results, however, is the potential for the contamination by non-stellar light, which may bias the stellar masses for the brightest AGN. To investigate this issue, we plot the measured stellar mass against the J -band absolute magnitude for all galaxies

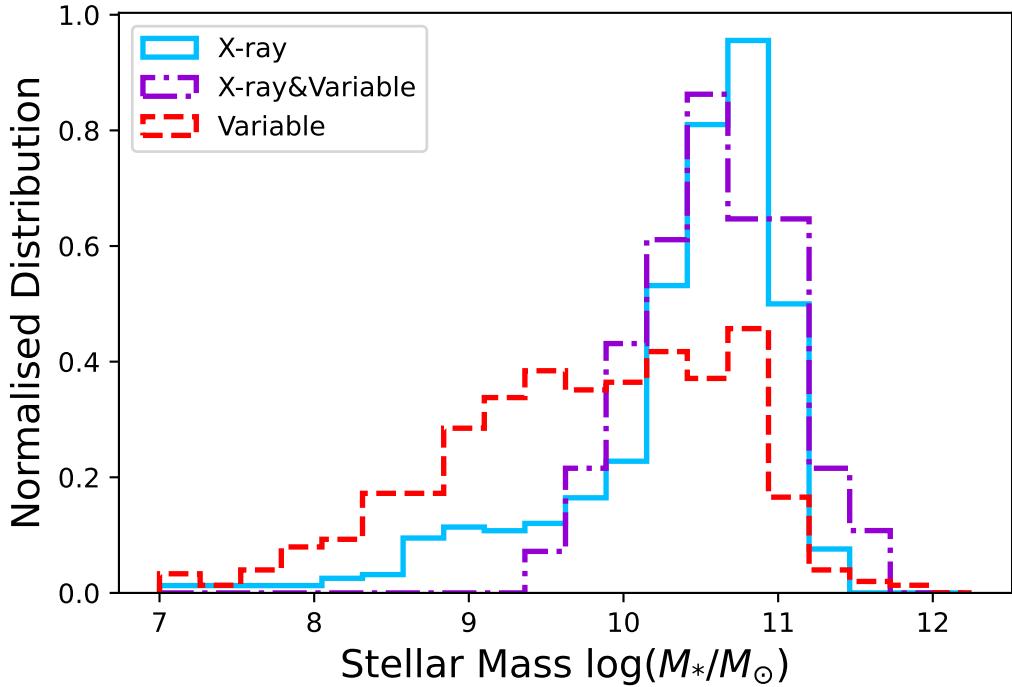


Figure 4.3: Normalised histograms showing the distribution in stellar mass of active galaxies in the sample. Galaxies are separated according to detection method, where the blue solid-lined histogram represents X-ray selected active galaxies, the red-dashed histogram shows objects classified as hosting variable AGN only, and the purple-dotted histogram shows objects that were detected using both methods. A Kolmogorov-Smirnov test confirms that the variability detected sample has a significantly different distribution in stellar masses compared to the X-ray population, rejecting the null hypothesis that they are drawn from the same underlying mass distribution with a significance of > 99.99 per cent.

in the field in Figure 4.4.

Here we find the active galaxies to broadly exist in two regimes: one where the measured magnitude of the galaxy is much brighter than inactive galaxies of a similar mass, and one where the measured magnitude of the galaxy is similar to inactive galaxies of a similar mass. From this bimodality, we can assume that the observed light from the active galaxies that lie within the locus formed by the inactive galaxies are dominated by the hosts' stellar light, and as such the measured host galaxy parameters are minimally impacted by the presence of an AGN. On the other hand, active galaxies that are much brighter than their inactive counterparts of similar mass likely have emission that is dominated by the AGN, suggesting the presence of a quasar.

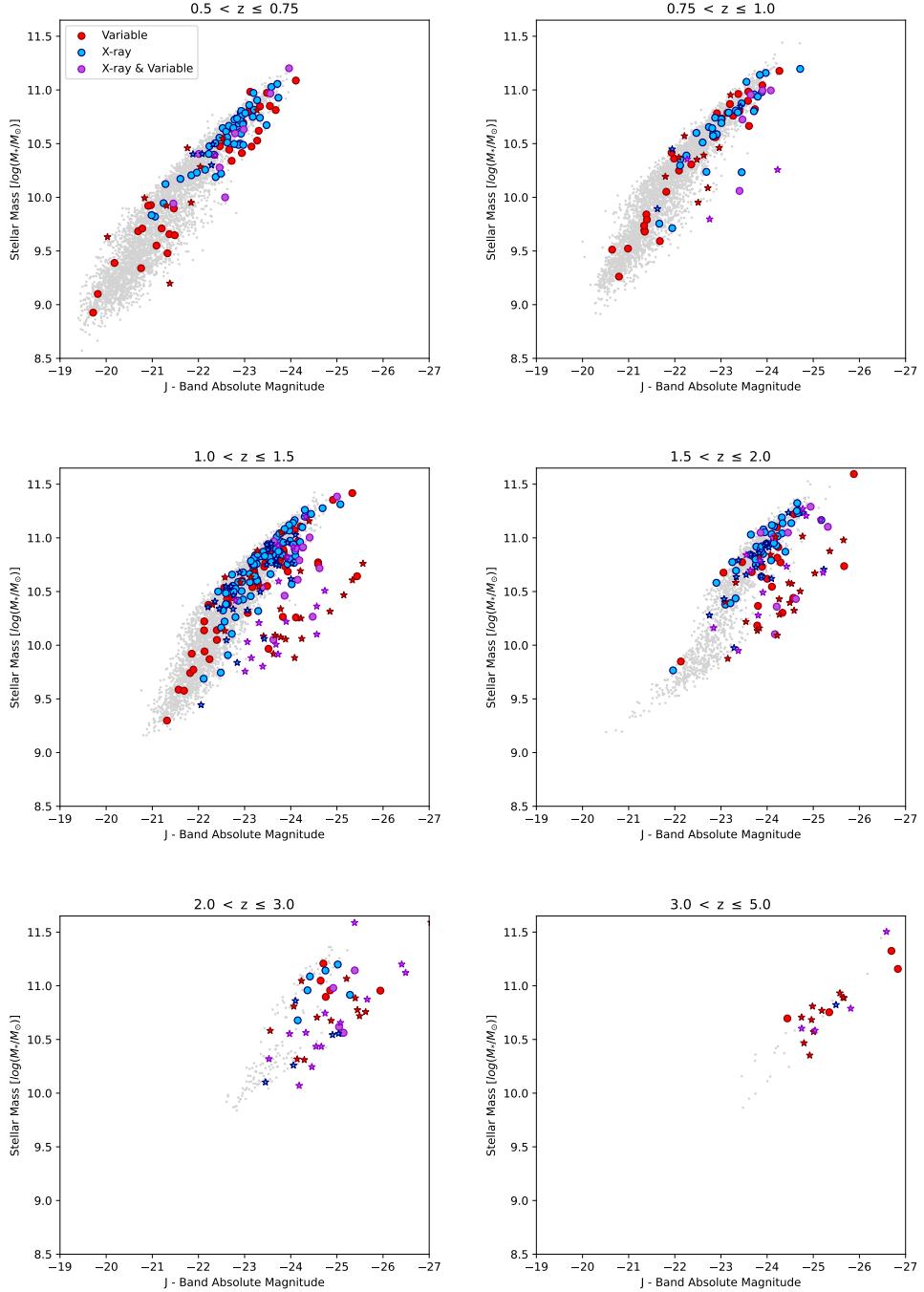


Figure 4.4: Stellar mass vs. J -band absolute magnitude for X-ray detected active galaxies (blue points), variability-detected active galaxies (red points) and dual-detected active galaxies (purple points) as a function of redshift. Inactive galaxies are plotted as grey points and all galaxies lie above the 90 per cent mass completeness limit. Corresponding coloured stars indicate an active galaxy that has a stellarity index of $\geq 90\%$ according to the CLASS STAR parameter from SExtractor.

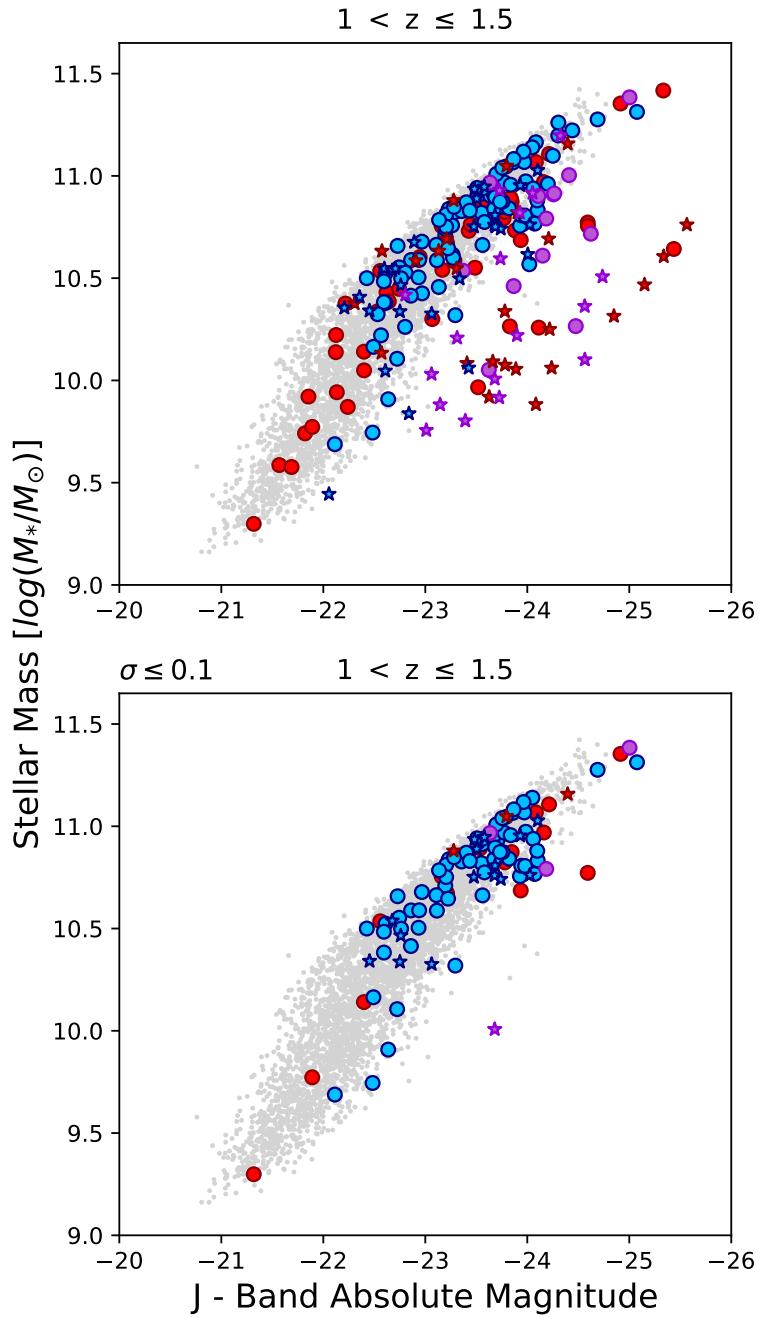


Figure 4.5: Stellar mass vs. J -band absolute magnitude for galaxies between $1 < z \leq 1.5$. Plotted are active galaxies (AGN) that are either X-ray-detected (blue points), variability-detected (red points), or dual-detected (purple points), as well as a comparison sample of inactive galaxies (grey points). Correspondingly-coloured stars indicate an active galaxy that has a stellarity index of $\geq 90\%$ according to the CLASS STAR parameter from SExtractor. The bottom plot is as the top, but only shows active galaxies with (intrinsic) variability amplitudes of $\sigma_J \leq 0.1$. All galaxies plotted lie above the 90% mass completeness limit.

To test if these abnormally bright sources are quasars, we investigate their morphology using the K -band stellarity index from SExtractor, which (after removing galactic stars) provides a good indication that an AGN is dominating the emission from a source. From this we find that a majority of the bright sources appear point-like, which suggests the AGN emission is outshining that of the host galaxy.

These empirical trends are likely to be caused by a combination of factors. In particular, the stellar masses are obtained by fitting stellar population models, without an AGN component. If a Type-1 quasar dominates the SED, the best fit is likely to be an extremely young stellar population, yielding a very low mass-to-light ratio. As a secondary issue, the variable AGN were identified in the observed J and K bands, while observations at longer and shorter wavelengths were taken at different epochs. Therefore, as a selection effect, we might expect AGN to be brighter than average in the J and K bands, which would enhance their near-infrared luminosity relative to the stellar mass determined from the 12-band SED.

Furthermore, to investigate if a quasar is present within the identified bright, point-like sources, in Figure 4.5 we remove the objects with the largest variability amplitudes, on the assumption that the NIR light in such objects must be dominated by the AGN. Figure 4.5 shows the stellar mass vs. magnitude for galaxies with redshift $1 < z \leq 1.5$ both before and after requiring galaxies to have an intrinsic variability amplitude of $\sigma_Q \leq 0.1$. Here we find that applying this limit primarily removes the point-like sources that are much brighter than inactive galaxies of a similar mass. In the case of objects detected via their X-ray emission, imposing this limit does not have a significant effect on the active galaxies that lie within the locus formed by inactive galaxies, but largely removes the bright, point like sources. It is therefore likely that the bright point-like active galaxies are indeed quasars, where the powerful AGN is driving significant variability and dominating the NIR light.

4.3.2 Stellar mass functions

To fairly compare the host properties of the active galaxies, we remove the quasars from the distributions to avoid significant amounts of non-stellar light impacting measurements. To do this we generate a contour that encompasses 95% of the inactive galaxies in each bin seen in Figure 4.4, and we require the active galaxies in corresponding bins

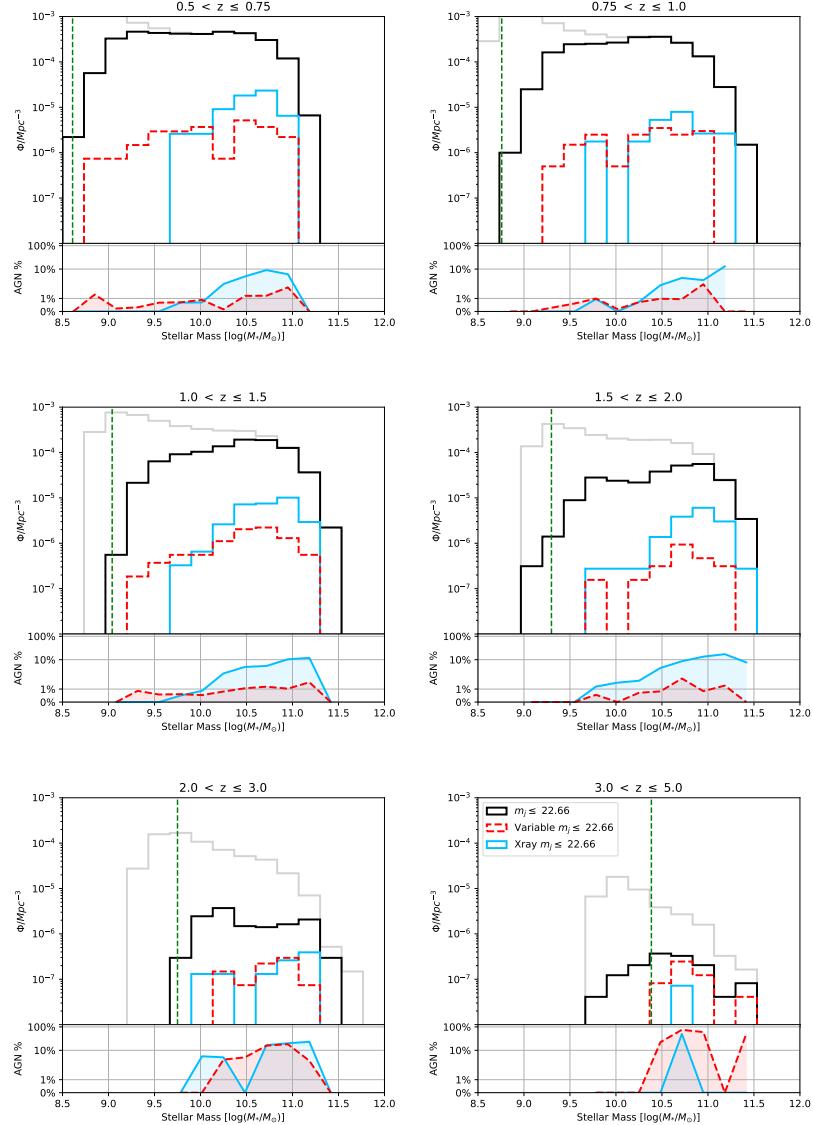


Figure 4.6: Stellar mass functions as a function of redshift. The grey histogram represents the mass distribution for all galaxies within the field except for quasar-like AGN, which have been removed. The black histogram shows the same but for galaxies with J -band apparent magnitudes $m_J \leq 22.66$ which ensures that a variability of 20% or higher will be consistently detectable. The dashed red histogram is as the black but shows only variability detected active galaxies. The solid blue histogram shows X-ray detected active galaxies, again with candidate quasars removed. X-ray detections were calculated using galaxies from the X-UDS imaging region and scaled to match the variability detected galaxies. The corresponding coloured distributions below each stellar mass function shows the percentage of AGN for that redshift bin as a function of stellar mass. The 90% mass completeness limit is denoted by the vertical dashed green line.

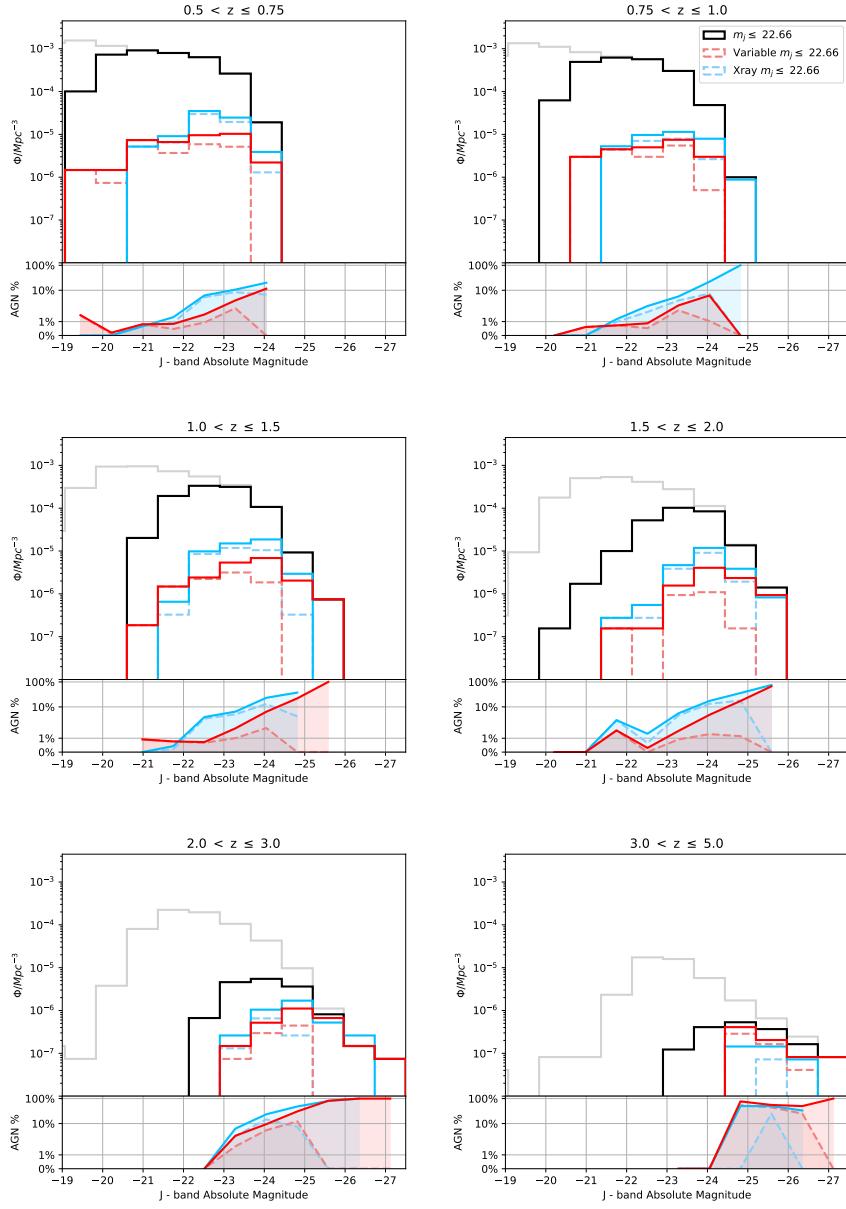


Figure 4.7: Luminosity functions as a function of redshift. The grey histogram represents the luminosity distribution for all galaxies within the field, while the black histogram shows the same but for galaxies with J -band apparent magnitudes $m_J \leq 22.66$. The solid red and blue histograms are as the black but only shows variability and X-ray detected active galaxies, respectively. Lighter coloured, dashed histograms show the active galaxy luminosity functions with quasars removed. X-ray detections were calculated using galaxies from the X-UDS imaging region and scaled to match the variability detected galaxies. The corresponding coloured distributions below each luminosity function shows the percentage of AGN for that redshift bin as a function of decreasing J -band absolute magnitude.

to lie within the contour formed by the inactive galaxies. Applying this cut to the data removes 75 (12%) of the variable AGN from the sample, 35 (5%) of the X-ray AGN and 55 (51%) of the dual-detected AGN. Using the remaining galaxies, we generate the stellar mass functions shown in Figure 4.6. Here the grey line shows the mass function for all galaxies in the data and the solid black line shows the population of galaxies with $m_J \leq 22.66$. As discussed in Section 3.4, this magnitude limit ensures that a variability of 20% or higher will be consistently detectable for all galaxies.

With the quasars removed, we find that the fraction of galaxies with X-ray detected AGN increases with increasing stellar mass of the host galaxy, whereas the detection rate of NIR variable AGN is largely flat, remaining on the order of $\sim 1\%$ of galaxies regardless of the stellar mass of the host. This difference is consistent up to $z \approx 2$, where enough galaxies above the mass completeness limit are present to draw reasonable conclusions. We conclude that, across a broad redshift range, NIR variability allows for the identification of AGN in much lower mass host galaxies compared to X-ray selection.

4.3.3 Luminosity functions

In this section we investigate the luminosity functions of objects derived from the two methods of AGN detection, without applying any quasar filtering. This will provide a check on the influence of AGN light on the derived properties of these objects, which will be particularly significant in future situations where we may lack the range of spectral data and spatial resolution required to filter out quasars. In Figure 4.7, we plot the J -band absolute magnitude as a function of redshift for the detected active galaxies.

Here, we find that both methods detect much more similar distributions of objects, with the fraction of AGN increasing with luminosity whichever technique is used. This increase reflects the fact that the luminosity functions are strongly influenced by the contribution of AGN light, with brighter AGN more likely to be detected by either method. Without the auxiliary information we have employed in this work, it is not possible to reliably disentangle host galaxy and AGN properties from such data.

4.4 Conclusions

In this study, we use the long-term near-infrared variability of objects seen in the UKIDSS Ultra Deep Survey as an alternative approach to finding active galactic nuclei. We then compare the sample of AGN revealed in this way to those found using a more conventional X-ray-based method in the same field.

We find that the variability approach detects a distinct population of AGN, with an overlap of only 37 per cent between the two samples. An analysis of the X-ray-to-optical luminosity ratio finds the IR-variable AGN appear relatively X-ray quiet. Whether these AGN are intrinsically X-ray faint or heavily obscured is unclear, and will be the subject of future study.

After excluding quasar-like objects, whose AGN brightness means that we cannot reliably measure properties of the underlying host galaxy, we find that IR variability systematically detects AGN in galaxies with lower stellar masses than X-ray-detected objects. Comparing their mass functions, we find that IR-variable AGN are hosted in $\sim 1\%$ of galaxies of any mass, whereas the percentage of X-ray AGN detected strongly increases with increasing stellar mass of the host galaxy. This distinction seems to be independent of redshift out to the $z \sim 2$ probed by these data. One plausible explanation for the difference would be related to extinction: if low-mass hosts tend to systematically contain more heavily obscured nuclei, that might explain why AGN in such galaxies are more readily detected by their infrared variability than by their extincted X-ray emission. In future work we will explore the dependence of variability on redshift and hence on rest-frame waveband, to explore the implications for the origin of the AGN emission.

In seeking such physical explanations, we need to be able to reliably separate AGN and host properties. The significance of the contribution of AGN light to distorting our understanding of their host galaxies is underlined by the rather different results we obtain by simply studying their luminosity functions, in which a higher fraction of AGN is found in more luminous objects, whichever method is used to identify them. This distinction arises from the fact that the luminosity function, particularly when including quasar-like objects, reflects the properties of the AGN as well as their hosts. Clearly, some care is needed in interpreting such composite data, and additional spectral and spatial information is vital.

These results indicate that multiple approaches to AGN detection are required to obtain a complete census of such objects. With upcoming deep, wide-field surveys such as EUCLID and LSST, which will be obtained over extended periods, long-term variability offers an important approach to identifying AGN missed by other methods, which is key to a more detailed understanding of the prevalence of these objects and their role in galaxy evolution.

Chapter 5

Paper 2

5.1 Introduction

Infrared (IR) emission has been observed in active galaxies since the late 60's ([Pacholczyk & Wisniewski 1967](#); [Low & Kleinmann 1968](#)), and this sparked interest into the properties of AGN in this regime. A key question was to determine if thermal or non-thermal emission processes generated the infrared light, as each type of emission implies different underlying mechanisms occurring in the AGN.

[Elvis et al. 1986](#), was able to fit a single power law to the spectral energy distribution (SED) of six of the quasars studied in their research. From this, they suggested that AGN emission from the X-rays to the infrared is driven by a single, non-thermal mechanism. Likewise, in measuring the mid-infrared spectrum of AGN, [Cleary et al. 2007](#) found that non-thermal, synchrotron emission significantly contributed to the radiation measured in such bands.

Other studies, however, have found thermal processes to better explain IR emission in active galaxies. [Rees et al. 1969](#) was able to model IR radiation from $2.2\mu\text{m}$ - $22\mu\text{m}$ as radiation generated by the heating of dust via a nuclear UV or optical source. [Barvainis 1987](#) completed similar work, developing a circumnuclear dust-heating model for IR AGN radiation that was able to predict the temperature, composition and orbital distance of the dust.

In addition to model predictions, there is significant observations of the IR spectra in the literature. [Rieke 1978](#) wrote one of the first reviews on the topic, collating IR measurements of 53 Seyfert galaxy spectra from various sources. These observations ranged from $1\mu\text{m}$ and $10.6\mu\text{m}$ and concluded that the infrared output likely originates from UV emission re-radiated by dust.

[Sanders et al. 1989](#) made continuum observations from 0.3nm to 6cm of 109 quasars. They argue that almost all of the infrared emission can be attributed to re-radiation of bluer light by dust in a disk orbiting at radii consistent with those predicted in [Barvainis 1987](#).

[Shi et al. 2005](#) reports on the infrared photometry of 20 radio-loud quasars. Inspecting this emission, they found a majority of the far-infrared radiation originated from dust heated by the AGN and star formation within the active galaxy. They also state that the

AGN contribution to heating dominates over star formation driven heating in a majority of the sources.

[Dicken et al. 2009](#) also studies the far-infrared spectrum of 46 active galaxies. They quote circumnuclear dust at being the primary heating mechanism for the thermal radiation in the systems, as well as rule out non-thermal synchrotron contamination as a source of infrared radiation.

In addition to spectral data, other approaches to measuring the nature of the infrared AGN spectrum have been made. $2.2\mu\text{m}$ variability was measured in [Hunt et al. 1994](#) for 9 Seyfert galaxies. No evidence of the short-term near-infrared (NIR) variability possible only in the non-thermal radiation scenario was found.

Furthermore, [Rieke & Lebofsky 1981](#) examined the continuum of NGC 4151, one of the six original Seyfert galaxies ([Seyfert, 1943](#)), for signs of polarisation in the light that would occur in synchrotron emission. The polarisation of the $1\mu\text{m}$ - $4\mu\text{m}$ radiation was found to be negligible in this galaxy, and they concluded that it was more likely that infrared emission arose from dust heated by a non-thermal source.

Though it is now accepted that AGN emission varies in flux in every band it has been observed in ([Edelson et al. 1996](#); [Collier et al. 1999](#); [Cackett et al. 2021](#)), very few variability studies have been completed on the origin of infrared emission in active galaxies. Though [Hunt et al. 1994](#) rules in favour of the thermal scenario, the research is limited to a small galaxy sample with light curves that are not well sampled.

The lack of research into infrared variability is likely due to the time-cost of the observations, as the AGN variability timescale increases wavelength (e.g., [Berk et al. 2004](#)), causing significant IR flux changes to occur over the course of many years. AGN emission theory, however, maps variability to different structures within the AGN itself, with variability in higher frequencies originating closer to the core of the system (e.g., [Bianchi et al. 2022](#)).

[Clavel et al. 1989](#) measured the far-UV, optical and infrared variability of the active galaxy Fairall 9. Through investigating the nature of variability in different wavelengths, they found optical and *J*-band variability to be diluted by starlight, but otherwise in phase with UV variability. Variations at longer wavelengths, such as the *K* and *L*-bands however, were noticeably out of phase with measured fluctuations in the bluer bands.

This identified a possible turnover in emission mechanisms between the J and K bands in active galaxies.

In this chapter, we investigate the properties of 601 active galactic nuclei between $0 < z \leq 5$, selected through long-term near-infrared variability in the J and K -bands. We compare the rest-frame features of the galaxies to each other as well as to a sample of X-ray selected AGN split by hardness ratio as a proxy for obscuration. From this we determine if AGN that are significantly variable in the K -band show features consistent with emission from the thermal re-radiation of bluer light by dust, and we investigate if these same features are present in AGN selected in the J -band.

5.2 Variability dependence on wavelength

We begin by investigating how the variability amplitude of the active galaxies changes with wavelength. To do this, we plot the variability amplitude in the J -band (σ_J) vs the K -band (σ_K) in Figure 5.1. Here galaxies are split by the photometric band the AGN was selected as being significantly variable in.

We first find that all the galaxies show a positive correlation in σ_J and σ_K , regardless of the band the AGN was selected in, however clear differences in the chromatic nature of the AGN becomes apparent when splitting the measurements by the detection band. AGN selected in the J -band show enhanced variability in the bluer, J -band compared to the K -band. This anti-correlation of variability amplitude with wavelength is in agreement with previous work in the UV (Paltani & Courvoisier, 1994) and the optical (Cid Fernandes et al. 1996, Berk et al. 2004, MacLeod et al. 2010, Zuo et al. 2012).

Measurements for K -band selected AGN contrast this however, with larger fractional variability being seen in the redder K -band.

The result that K and J -band selected active galaxies show opposite correlations with wavelength could be due to selection bias, as one would expect the variability amplitude to be larger in the detection band. To determine if this is the case, we inspect the dual-band detected active galaxies (AGN measured as being significantly variable in both the J and K -photometric band). If the detection band does bias the variability amplitude measurement, we expect the comparison of σ_J to σ_K to be unity in the dual-band detected

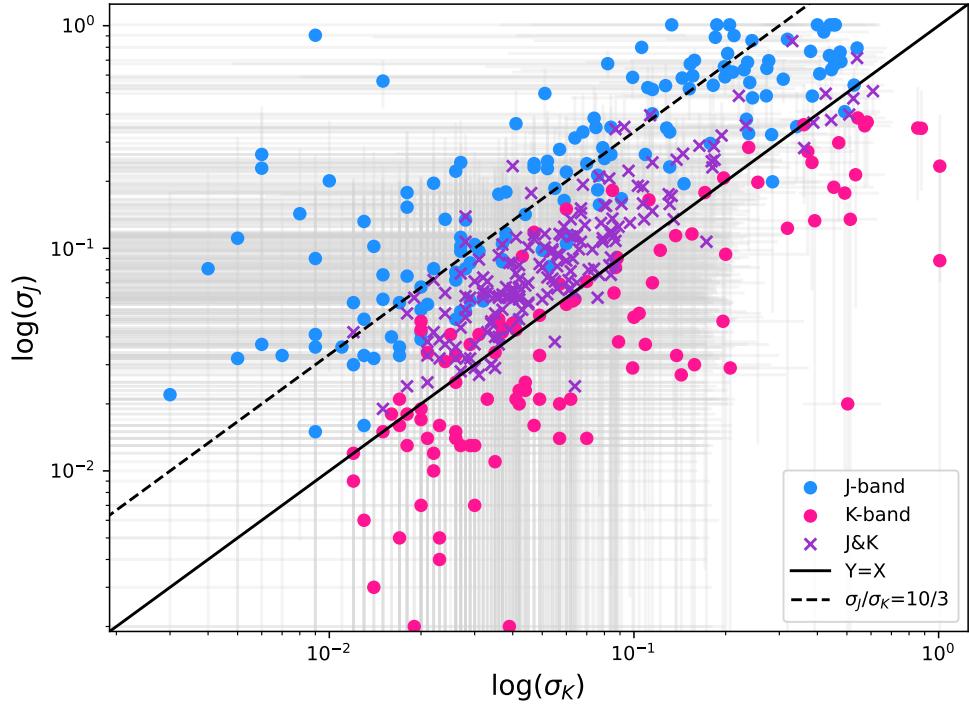


Figure 5.1: J vs K -band variability amplitude for variability detected AGN. AGN are split by detection band with blue dots showing AGN variable in the J -band only, pink dots showing K -band only variables and purple crosses denoting dual-band detected AGN. The solid black line shows unity and the black dashed line is the expect variability ratio of 10/3 based on the modeled IR variability spectrum in [Meusinger et al. 2011](#).

sample. Measurements of this however (Fig. 5.1), finds these galaxies anti-correlate wavelength and variability amplitude, in agreement with the J -band variable AGN in this sample.

5.2.1 Infrared variability spectrum

In [Meusinger et al. 2011](#), the AGN variability spectrum is calculated to change as

$$\sigma_\lambda \propto \lambda^{-2}. \quad (5.1)$$

Here λ is the wavelength and σ is the variability amplitude measured at wavelength λ . Applying this relation, we find the expected J to K variability amplitude to be $\approx 10/3$. This value is plotted in Figure 5.1, and predicts that a given, unobscured AGN should be more variable in the J -band than the K -band.

Inspecting where the measured values lie in comparison to this, finds differences when splitting the variability detected groups by detection band. The J -band detected group best follows the model prediction, with the increased and dominant σ_K contribution in dual and K -band detected AGN respectively lowering the distributions.

The anti-correlation of σ with wavelength in the dual-band detected sample as well as there being clear differences in the σ_J/σ_K distribution for the AGN when split by detection band implies it is more likely the positive correlation of σ_K and wavelength for K -band detected AGN is due to some physical processes in the system over sample detection bias.

5.3 Origin of Variability in AGN

We next investigate the rest-frame (RF) emission of the 601 active galaxies selected by K and J -band variability in this research.

We plot the ratio of the measured K to J -band variability amplitude vs redshift in Figure 5.2. Once again, samples are split by the photometric band they are variable in.

As found in section 5.2, AGN that are variable in the J -band only best follow the model (Meusinger et al., 2011), showing little evolution with redshift and largely lying on the expected σ_K/σ_J value of ~ 0.3 . Dual band detected AGN have a similar flat distribution with redshift, but are consistently offset from the model value, having larger values of σ_K/σ_J for all epochs studied.

The AGN variable in the K -band have the most unique behaviour of the active galaxies considered in this study. They show the highest σ_K/σ_J of any group as well as a clear decrease in the ratio with increasing redshift. In addition to this, most K -band only detections are found at RF-IR redshifts where J and dual-band detections show no obvious preference for the rest-frame emission.

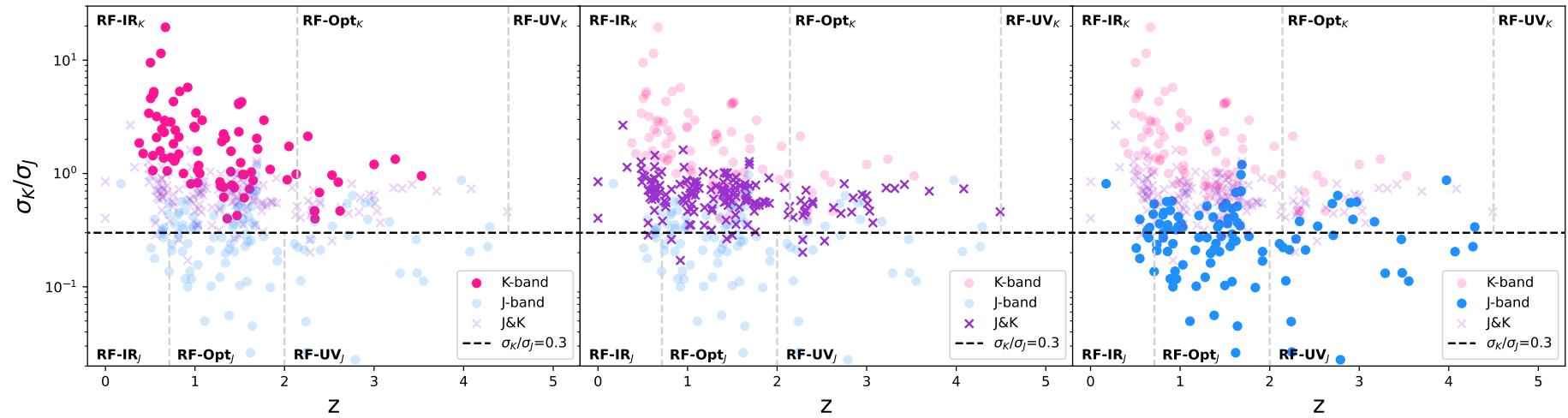


Figure 5.2: Ratio of K to J band variability amplitude vs redshift. Pink dots show K -band only detect active galaxies, purple crosses show dual band detected active galaxies and blue dots show J -band only detected active galaxies. Horizontal dashed grey line shows the model variability ratio of 0.3 as calculated according to the variability spectrum in [Meusinger et al. 2011](#). Vertical dashed light-grey lines denote the rest-frame emission ranges for the K and J -band above and below the $Y=0.3$ line respectively.

One explanation for these differences could be the presence of dust in the K -band AGN systems where there is less or none in the dual and J -band detected active galaxies. This would explain the shape and the location of the galaxies on the σ_K/σ_J - z plane as well as the positive correlation of variability amplitude and wavelength measured in the K -band detected sample. Variations in high redshift, dust obscured AGN would first be reddened, and then cosmologically redshifted to wavelengths beyond the K -band for all but local galaxies. The few K -band detections at RF-optical redshifts having σ_K/σ_J ratios close to the model value is in agreement with this, as this would occur if such objects were truly unobscured compared to their RF infrared counterparts.

This explanation is in agreement with the study of Seyfert galaxy Fairall 9 by [Clavel et al. 1989](#). They found the K -band variability of the AGN to be out of phase with UV, optical and J -band variability measures. From this, they interpreted K -band emission to probe thermal re-radiation of UV and optical emission from dust in an active galaxy whereas J -band emission originates from the accretion disk of the AGN.

5.4 Spectral Energy Distribution analysis

To investigate if variability in the K -band preferentially detects dust-reprocessed light from AGN, we investigate the spectral energy distributions (SEDs) of the galaxies. We introduce a comparative sample of active galaxies selected through X-ray emission and split these galaxies based on their hardness ratio (HR), as a proxy for the obscuration. In this research we consider X-ray soft galaxies ($HR < 0$) to be unobscured and X-ray hard galaxies ($HR \geq 0$) to be obscured.

5.4.1 Mass Matching

To compare the SEDs of the active galaxies we begin by mass matching the sub-samples of variability detected (K and J band detected) and X-ray selected (hard and soft) active galaxies. Galaxies are required to have masses within 1% of each other (Fig 5.3). This takes the sample from 180 to 74 detections in the K -band and 239 to 83 J -band detections as well as 323 to 247 X-ray hard AGN and 387 to 262 X-ray soft AGN.

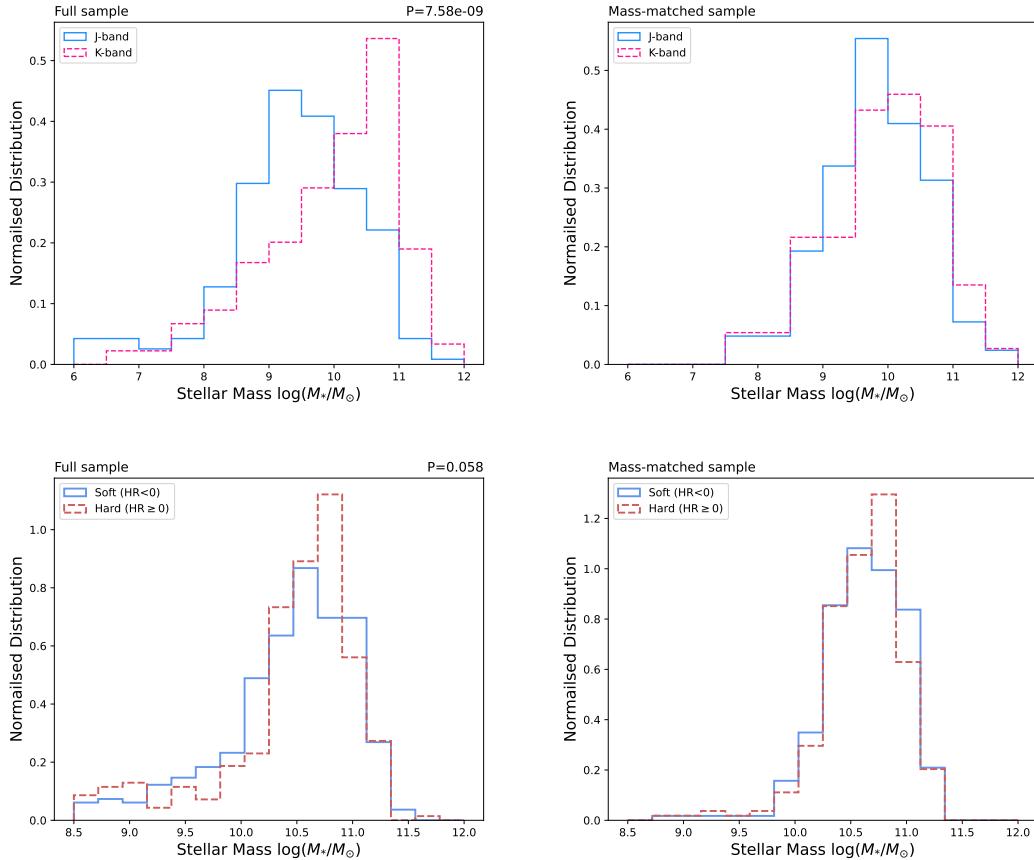


Figure 5.3: Stellar mass distributions of variability detected active galaxies split by detection band (top) and X-ray bright active galaxies split by hardness ratio (bottom). The left and right columns show the distribution prior to and after mass-matching respectively. Galaxy populations are mass matched within 1% of each other. In the top row, blue histogram shows the distribution for *J*-band detected active galaxies and the pink dashed histogram show the *K*-band detected active galaxies. In the bottom row the blue histogram shows X-ray soft active galaxies and the red dashed histogram shows the X-ray hard active galaxies.

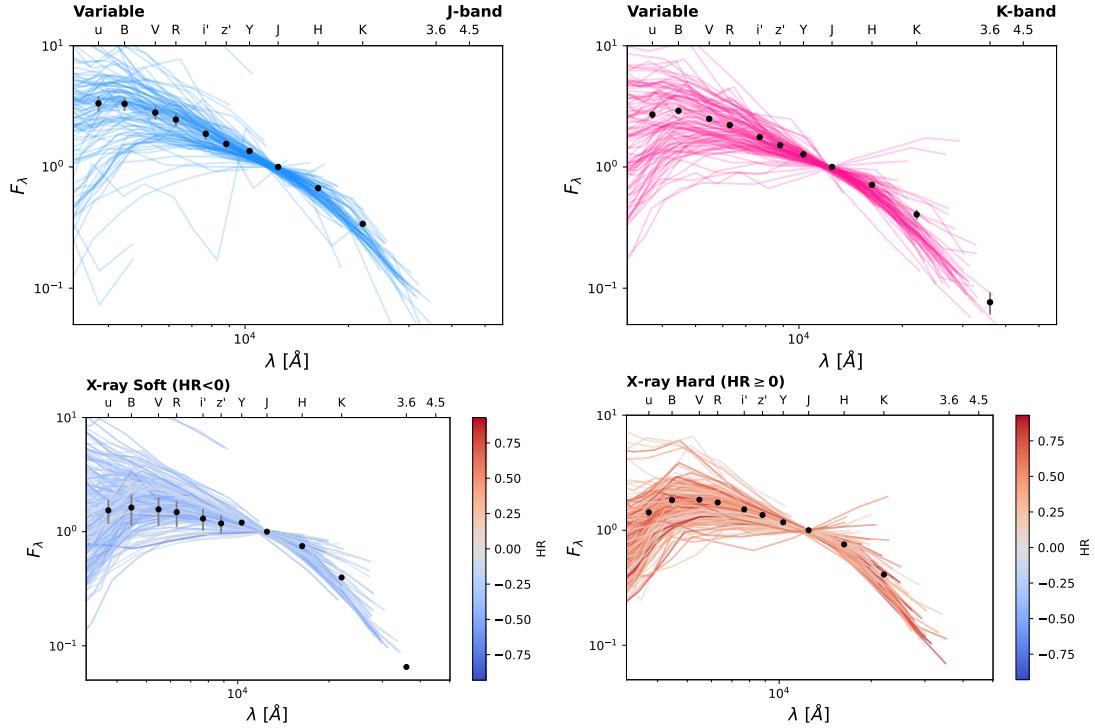


Figure 5.4: Rest-frame spectral energy distributions for the active galaxies studied in Section 5.4. Blue lines show active galaxies selected via J -band variability and pink lines show active galaxies selected in the K -band. The SEDs of X-ray detected active galaxies are split into X-ray soft ($HR < 0$) and X-ray hard ($HR \geq 0$) samples, and colour coded by hardness ratio on the same scale. All SEDs are normalised to unity in the J band, have black points at each photometric band denoting the average flux density value at that wavelength with the standard error on the mean being shown.

5.4.2 Calculating spectral energy distributions

To build spectral energy distributions (SEDs) for the galaxies (Figure 5.4), we take the 12 bands of photometry in the UDS (Chapter 2) and convert the measured AB magnitude values into flux densities (F_λ). We then shift the flux density measurements into the rest-frame based on the galaxy's redshift. These rest-frame SEDs are then normalised to unity in the J -band, where normalised, rest-frame values of flux density are calculated by interpolation at each of the 12 wavebands of the UDS photometry. These final flux density values are converted back into magnitudes where appropriate.

5.4.3 SED stacking

The SEDs of the samples consist of the 12 bands of photometry available in UDS data. We convert the measured AB magnitudes into flux densities and then shift each SED into the rest-frame based on the redshift of the galaxy. After this, each SED is normalised to unity in the *J*-band, and rest-frame flux densities were determined by interpolation at the 12 wavebands of the original measurements (Fig. 5.4).

Inspecting these SEDs, we find the largest differences in the ultraviolet, *U*-band. Visually, this is most apparent in the X-ray detected active galaxies, where X-ray soft galaxies show a range of *U*-band flux densities, but X-ray hard galaxies tend to be predominately faint in this filter. This difference can be seen by comparing the *U-B* colour of the galaxies. Figure 5.5 shows this comparison, and as seen visually in the overall shape of the SEDs, the distribution of the *U - B* colour in the X-ray hard active galaxies is redder compared to the X-ray soft active galaxies. A Kolmogorov–Smirnov (KS) test confirms that samples do not draw from the same underlying distribution.

Measurements of *U - B* for the *J* and *K*-band detected active galaxies finds a similar result, with the *K*-band detected sample having a redder *U-B* colour distribution compared to the *J*-band detected objects, and a KS test confirms the underlying colour distributions are different in each group. From this we conclude that variability in the infrared bands are able to provide information on the UV absorption of a galaxy.

5.5 Stellar Populations

In section 5.4 we find that the detection of band of the variable AGN is linked with the UV absorption of the active galaxy, however it is possible that differences in stellar populations drives the UV observations of the galaxies.

To investigate this, we plot the rest frame *UVJ* diagram of the galaxies in Figure 5.6. A *UVJ* colour-colour diagram is commonly used to separate out star-forming and quiescent galaxies (Wuyts et al., 2007), and we use the standard selection box as outlined in Williams et al. 2009 and Schreiber et al. 2015 to accomplish this.

Inspecting this diagram, we find no evidence that the differences in UV emission in the

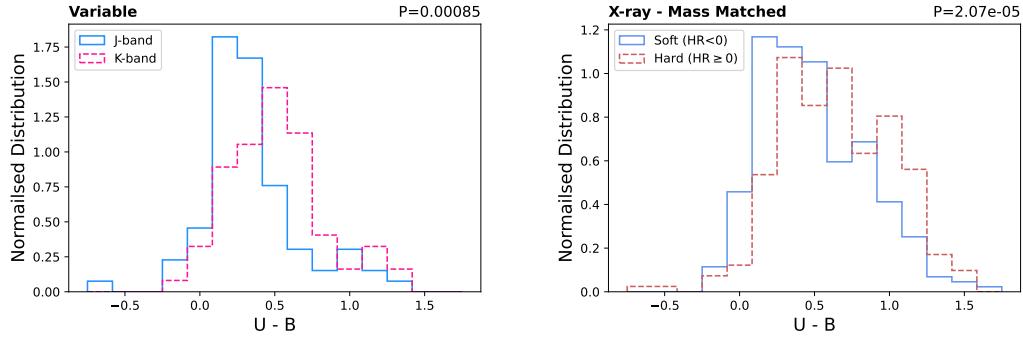


Figure 5.5: Rest frame $U - B$ colour distribution for variability detected (top) and X-ray detected (bottom) active galaxies. For the variability detected sample, the blue histogram represents active galaxies selected as variable in the J -band only, and the pink dashed histogram shows galaxies selected as variable in the K -band. For the X-ray detected sample, galaxies are split based on their hardness ratio, with X-ray soft galaxies denoted by the blue histogram and X-ray hard galaxies shown as the red dashed histogram. Sub-samples in each plot are mass-matched within 1 per cent of each other. The P-values shown are from a Kolmogorov-Smirnov test between corresponding sub-samples, and confirms that the K -band selected and X-ray hard active galaxies have significantly different underlying distribution of $U - B$ colour than the J -band selected and X-ray soft galaxies respectively.

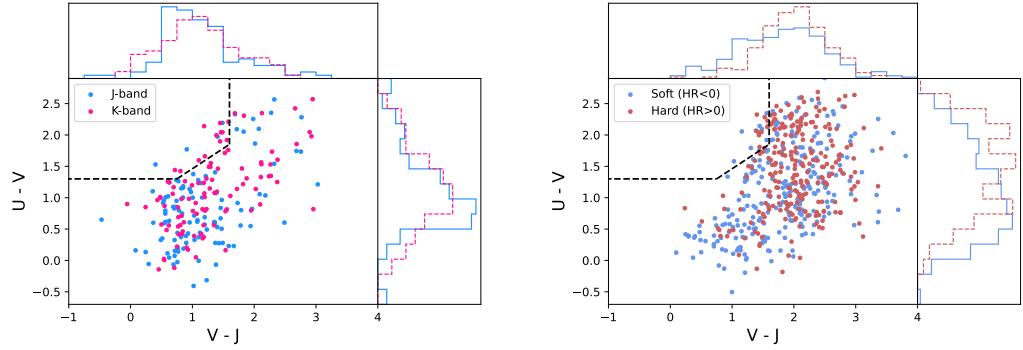


Figure 5.6: Rest-frame UVJ colour - colour diagram for mass-matched samples of variability detected (top) and X-ray detected (bottom) active galaxies. The black dashed line is as defined in Schreiber et al. 2015 and delineates quiescent galaxies from star-forming galaxies. Quiescent galaxies lie in the top left of the diagram. For the variability detected sample, blue points indicate J -band selected active galaxies and pink points show K -band selected active galaxies. In the X-ray detected sample, galaxies are split based on their hardness ratio, with X-ray soft galaxies shown as blue points and X-ray hard galaxies shown in red. In both plots, corresponding coloured histograms show the colour distribution.

active galaxies is due to the age of the stellar population. A vast majority of all mass-matched galaxies lie within the star-forming region of the diagram, with the distributions of the matched K and J -band detected galaxies being statistically similar according to a KS test and X-ray hard galaxies skewing red in both $U - V$ and $V - J$, which is known to indicate dust emission over older stellar populations (Williams et al., 2009). From this we find that differences in stellar age does not pose a plausible explanation the relatively faint UV emission in K -band selected active galaxies.

5.6 Variability timescale

As reviewed in Section 5.1, more evidence has been found in favour of IR AGN spectra beyond $\sim 2\mu\text{m}$ being generated via thermal re-radiation of optical and UV light by dust over a non-thermal emission scenario. We find differences in the chromatic nature of AGN variability amplitudes when splitting the active galaxies by selection band, and model comparisons confirm that observed results cannot be explained by selection bias in the sample. SED analysis reveals differing levels of UV emission in the J -band and K -band variable galaxies and a UVJ diagram confirms that the active galaxies have similar star-formation rates regardless of detection method.

The properties of the K -band detected AGN in these results favour a dust-driven, thermal emission model over a non-thermal emission model more consistent with the J -band detected sample.

To investigate the hypothesis that K -band variability does originate from a thermal emission scenario, we examine the timescale of the measured variability in the active galaxies. As expressed in Hunt et al. 1994, non-thermal, direct emission theories place no limit on the timescale of variability for a given wavelength. Thermal emission however, is dust-dependent and limited by the sublimation temperature and therefore orbital radius of the material, rendering variability on scales shorter than ~ 1 year impossible.

To do this, we compare the fractional variability amplitude measured on semester timescales to a modified fractional variability amplitude measured on month timescales, where semester effects have been removed (Section 3.5).

As shown in Figure 5.7, in the most variable J -band selected objects show variability on

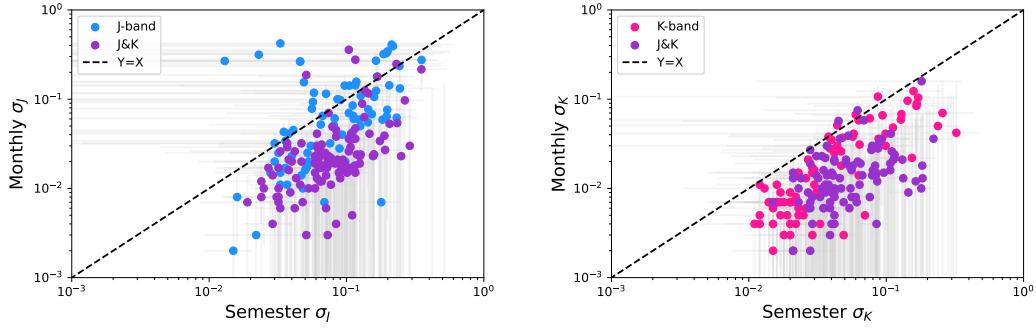


Figure 5.7: Modified monthly fractional variability amplitude vs semester variability amplitude for variability detected active galaxies. Measurements in the J -band are shown in the top plot and measurements in the K -band are shown in the bottom. J -band detected active galaxies are shown by blue points, K -band detected active galaxies are shown by pink points and active galaxies variable in both J and K photometric bands are shown as purple points. Light grey lines show the errors on measurements and the black dashed line traces unity.

the order of months, whereas the variability measured in the K -band is clearly skewed towards semester timescales. These same results remain true for dual-band detected AGN, where the J -band variability measurements for some of the most variable objects originates on shorter timescales, whereas the K -band amplitude requires several years to be observed.

We also find that these results link to observed properties in the active galaxies. Taking the comparison shown in Figure 5.7 and colour coding the points by the $U - B$ colour seen in Figure 5.5 we produce Figure 5.8. Here we find variability amplitude measurements anti-correlation with $U - B$ colour in the K -band selected variable AGN. No such relationship is observed in J -band detected objects and these results remain true when corresponding measurements from dual-band detected AGN are included. This provides more evidence in favour of a dust-reprocessing scenario in the K -band detected objects, as higher levels of obscuration would lead to the redder colours and dilution in variability amplitude as observed.

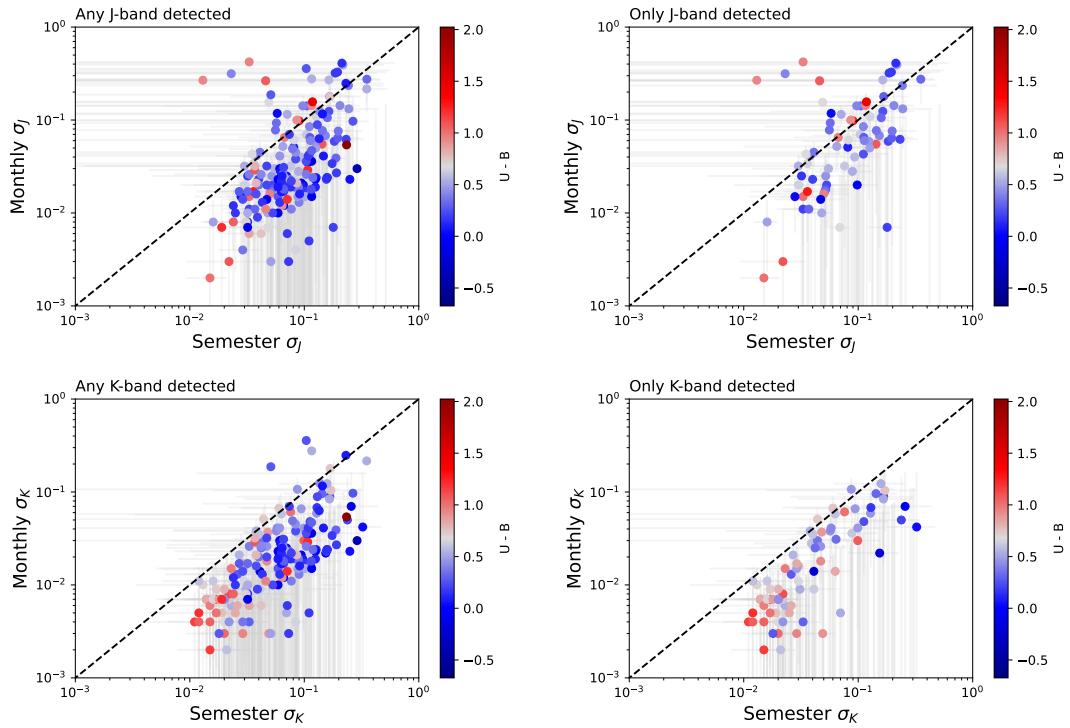


Figure 5.8: Modified monthly fractional variability amplitude vs semester variability amplitude for variability detected active galaxies. Measurements in the J -band are shown in the top row and measurements in the K -band are shown in the bottom row. The first column contains any galaxy detected as variable in the described photometric band and the second column shows galaxies only classed as variable in one band, with the aGN variable in both J and K -bands removed. Points are colour coded by the $U - B$ colour and light grey lines show the errors on measurements and the black dashed line traces unity.

5.7 Conclusions

In this research, we investigate the properties of AGN selected using long-term near-infrared variability in the J ($1.2\mu\text{m}$) and K ($2.2\mu\text{m}$) photometric bands. We compare these active galaxies to each other as well as to a set of X-ray hard and X-ray soft AGN as a proxy for dust obscuration in active galaxies.

We first study how the measured variability amplitude (σ_λ) changes with wavelength. From this we find variability in J -band detected AGN anti-correlates with wavelength, in agreement with previous optical and UV studies of AGN variability (Cid Fernandes et al. 1996, Berk et al. 2004, MacLeod et al. 2010, Zuo et al. 2012). Variability in AGN selected in the K -band however show the opposite trend, correlating variability amplitude and wavelength. To determine if these opposing results are intrinsic properties of the AGN, we investigate the nature of the variability amplitude in dual-band detected objects. These AGN are found to anti-correlate variability with wavelength, confirming that the differences observed in the J and K -band detected AGN are not due to selection biases in the samples.

We next investigate the AGN variability spectrum by comparing amplitude measurements split by detection band to the model spectrum presented in Meusinger et al. 2011. This model predicts that an unobscured AGN should be more variable in bluer bands, with the σ_K to σ_J amplitude ratio being $\approx 10/3$. We find that AGN detected from J -band variability largely match this prediction, with the observed ratio in other AGN decreasing with increasing dominance of the K -band detection.

Investigating the rest-frame origin of measured variability finds evidence that variability in different wavebands are generated in different ways. J -band detections best fit the accretion disk fluctuation model presented in Meusinger et al. 2011, having no preference for the rest-frame emission of the J -band flux as well as showing no evolution with redshift. Dual band detected AGN have similar properties, but are noticeably offset from the model-predicted σ_K/σ_J value, likely due to impact of K -band emission on the measurements. K -band detected AGN however, show significantly different features, with a majority for the galaxies originating at RF-IR redshifts and σ_K/σ_J decreasing over cosmic time. These properties could be explained by dust obscuration, as dusty higher redshift objects would have their intrinsic emission reddened beyond the K -band. In addition to this, K -band detected AGN in the RF-optical are found to have σ_K/σ_J similar

to model-expected value, which would occur if such objects were truly unobscured.

We inspect the spectral energy distribution of the galaxies for signs that IR emission is due to thermal reprocessing of bluer light in the K -band detected galaxies. Here, we take the sub-samples of active galaxies detected as variable in the J and K -band only, and mass-match them within 1 per cent of each other based on the measured stellar mass. In addition to this, we introduce a further, mass-matched, comparative sample of X-ray detected active galaxies, split by hardness ratio as a proxy for dust obscuration.

Comparisons of the SEDs of these galaxies finds different levels of UV emission, with K -band detected active galaxies appearing redder in the $U - B$ colour compared to J -band detections. Analogous results are found in the X-ray galaxies, with X-ray hard active galaxies having a redder $U - B$ distribution compared to the X-ray soft galaxies. UVJ measurements also confirm these differences are not due to the age of the stellar population in the galaxies.

Finally, we investigate the variability timescale to see if dust obscuration is a likely explanation for the differing properties of the sample. To do this, we compare the semester-scale variability amplitude to a modified month-scale variability amplitude, where semester effects have been removed. In doing this, we find the most variable J -band detections show variability on both short and long timescales, an effect that is expected if variability in these objects arises from accretion disk fluctuations that propagate out through the system. K -band variability, however, only occurs on semester timescales in line with a dust-reprocessing scenario of variability where shorter fluctuations would be impossible. Consistent results are observed in the corresponding measurements for dual-band detected AGN, which supports the dust-driven variability scenario for K -band detections.

Connecting the variability timescales to observed properties of the SEDs, an anti-correlation in amplitude and $U - B$ colour is found in the K -band sample, but no correlation between UV colour and amplitude is observed in the J -detections, with equivalent measurements from dual-band variable AGN following the same trends. Likewise, these results are in agreement with dust-reprocessing scenarios, where higher levels of dust contamination absorbs more UV light, diluting variability amplitudes in the process.

Overall, we conclude that splitting active galaxies found using long-term, near-infrared

variability, by the detection band finds active galaxies with systematically different properties. We confirm that the correlation of variability amplitude and wavelength is opposite for J -band detected and K -band detected AGN and we find K -band variable active galaxies to be consistently UV faint compared to galaxies variable in the J -band.

The observed properties of K -band detected active galaxies suggest the IR spectrum is dominated by thermal emission from hot dust over non-thermal radiation processes. These results are consistent with [Clavel et al. 1989](#), and therefore if the NIR spectrum of AGN can be attributed to a combination of thermal and non-thermal emission processes, thermal emission begins to dominate over non-thermal emission between the rest-frame J and rest-frame K -band.

Chapter 6

AGN host stuff

Chapter 7

Conclusions and Future Work

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