3C273 with NuSTAR

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Abstract

The results obtained from ten X-ray observations spanning 2015-2021 on the quasar 3C273 performed by NuSTAR are presented here. The aim of this paper is to study the short and long-term evolution of the spectrum of 3C273. Evidence of complex spectral features such as soft excess, Fe K emission line, flux and spectral correlated variability are presented. We explain these features as arising from the structure of the accretion disk and coronal emission.[1] The combined spectrum is well-described by an exponentially cutoff power-law which self-consistently includes the iron line and a weak reflection component from cold, dense material (pexmon). By comparing each NuSTAR observation when fit with the pexmon model, we can investigate the spectral variability of 3C273 over time. At radio to millimeter and at gamma-ray energies, flares from the relativistic jet dominate the variability of 3C273. Considering Fermi and Bats observations on 3C273, it appears that jet activity affected the NuSTAR data in the X-ray band. Correlation studies on the source indicate a direct relationship between the cutoff energy and photon index as well as an inverse correlation between the flux and photon index. Finally, by examining the long-term trend of the spectral index of 3C273, we can see that the source has softened over time.

Background

3C273 and the Relativistic Jet

3C273 is one of the nearest and brightest quasars, featuring a relativistic jet showing superluminal motion. The jet is collimated from the radio to X-ray bands, allowing for a detailed study of the physical properties of the AGN at regions close to the supermassive blackhole.[2] At a redshift of z = 0.158, 3C273 has been extensively studied since its discovery and is highly variable across all energies. The source has been actively monitored since its discovery in 1963 and exhibits a long-term spectral evolution as well as short term variations. 3C273 emits strongly in the γ-ray band and has been consistently observed by Fermi over the years. At γ-ray energies, flares from the jet dominate the variability of 3C273 and Fermi observations on the source reveal interesting γ-ray flares from the jet[1].

Properties of an AGN

The spectrum of 3C273 reveals complex spectral features including a weak reflection component and a weak neutral iron line. The accretion disc emits photons which are inverse

Compton scattered by a corona of hot electrons surrounding a super massive black hole. These inverse Compton scattered photons are what form the primary X-ray continuum which can be fitted to a power-law. Reflection off an accretion disk or distant material gives rise to a weak reflection component. The reflection component presents an iron line at 6.4 keV. The continuum shows a high energy rollover which depends on the temperature and optical depth of the hot electron plasma composing the corona[1]. Understanding these properties allows us to fit the spectrum to an appropriate model to further study the source.

Fitting the Spectrum and Objectives

I took 10 NuSTAR observations on 3C273 spanning the years 2015-2021 to observe the variability of the source and look for correlations. I later looked at the Fermi and Swift/BATS light curves to compare the flux at the different observation times. Table 1 lists the observations ID's and exposure times for the observatories used.

Table 1: Observation Log

Instrument	Start Time	OBSID	Exposure(s)
NuSTAR	2015-07-13 14:01:08	10002020003	49414
	2016-06-26 19:11:08	10202020002	35411
	2017-06-26 17:41:09	10302020002	35398
	2018-05-19 18:01:09	80301602002	60763
	2018-06-02 02:01:09	10402020002	16089
	2018-06-15 04:31:09	10402020004	21183
	2018-07-04 17:21:09	10402020006	40317
	2019-07-02 07:51:09	10502620002	49410
	2020-07-06 04:56:09	10602606002	44018
	2021-06-09 18:36:09	10702608002	36041
Instrument	Start Time	Stop Time	Exposure(years)
Fermi	2008-08-09	2021-08-24	13
Swift/BATS	2005-02-15	2021-08-15	16

I first combined the 10 NuSTAR observations using addascaspec (a perl script used to combine spectra) and looked at the combined spectrum. The continuum, as seen in Figure 1, indicates that the presence of the iron line at 6.4 keV is very weak. When fitting the combined spectrum to an absorbed power-law model over the 3-75 keV band, visual inspection of the residuals revealed that there were significant deviations from the power-law above 25 keV. I then fit the spectrum to the pexrav, pexrav+zgauss, and pexmon model and looked at the resulting residuals and chi-squared values[1]. Table 2 lists the best fit parameters obtained from these models. All three models yielded similar parameters within error. We deduced that the best fit was the pexmon model: an exponentially cutoff power law with a weak reflection component.

Figure 1: Combined Spectrum

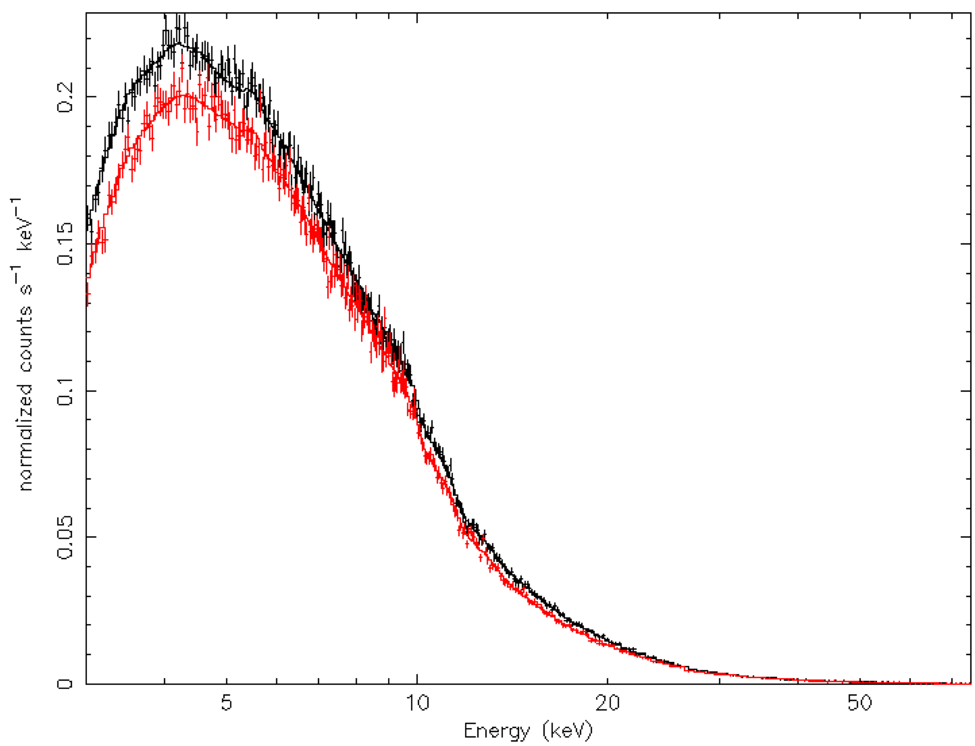


Table 2: NuSTAR Continuum Spectral Fits

Parameter	w/o jet
zpowerlaw	(3595 dof)
χ2red	1.125
Γ	1.66± 0.003
pexrav	(1928 dof)
χ2red	1.015
Γ	1.62± 0.01
E cutoff	218^{+34}_{-26} keV
Relative reflection	.104± 0.03
pexrav+zgauss	(1926 dof)
χ2red	1.010
Γ	1.62± 0.003
E cutoff	218^{34}_{26}
Relative reflection	.099± 0.03
Line Energy (fixed)	6.40 keV
Line width σ	$.43^{+1.05}_{-.32}$
pexmon	(1928 dof)
χ2red	1.010
Γ	1.62± 0.009
E cutoff	216^{32}_{25}
Relative Reflection	.063± 0.02

Individually, I fit the 10 NuSTAR observation to the pexmon model in order to investigate 3C273 over the years. The key parameters compared between all observations with the pexmon fit were the photon index, the E-folding value and the relative reflection component. The results showed a long-term trend in the spectral index, a direct relationship between the cutoff energy and photon index as well as an inverse correlation between the flux and photon index.

Presence of the Jet

I first investigated the flux in the 3-75 keV band as a function of time. In 2016, there is a notably high data point as seen in Figure 2. When looking at where all the observations fell on the Fermi light curve (Figure 3) we found that there was a high data point that occurred within the time frame of the 2016 NuSTAR observation. We know that at radio to millimeter and at gamma ray energies, flares from the jet dominate the variability of 3C273[1]. The Fermi data indicates that in 2016 there was flaring activity from the jet at GeV energies meaning there was activity occurring with the jet. This suggest that jet activity is affecting the NuSTAR X-ray data, and that we aren't simply seeing AGN emission, but jet emission as well.

Figure 2: Flux Over the Years

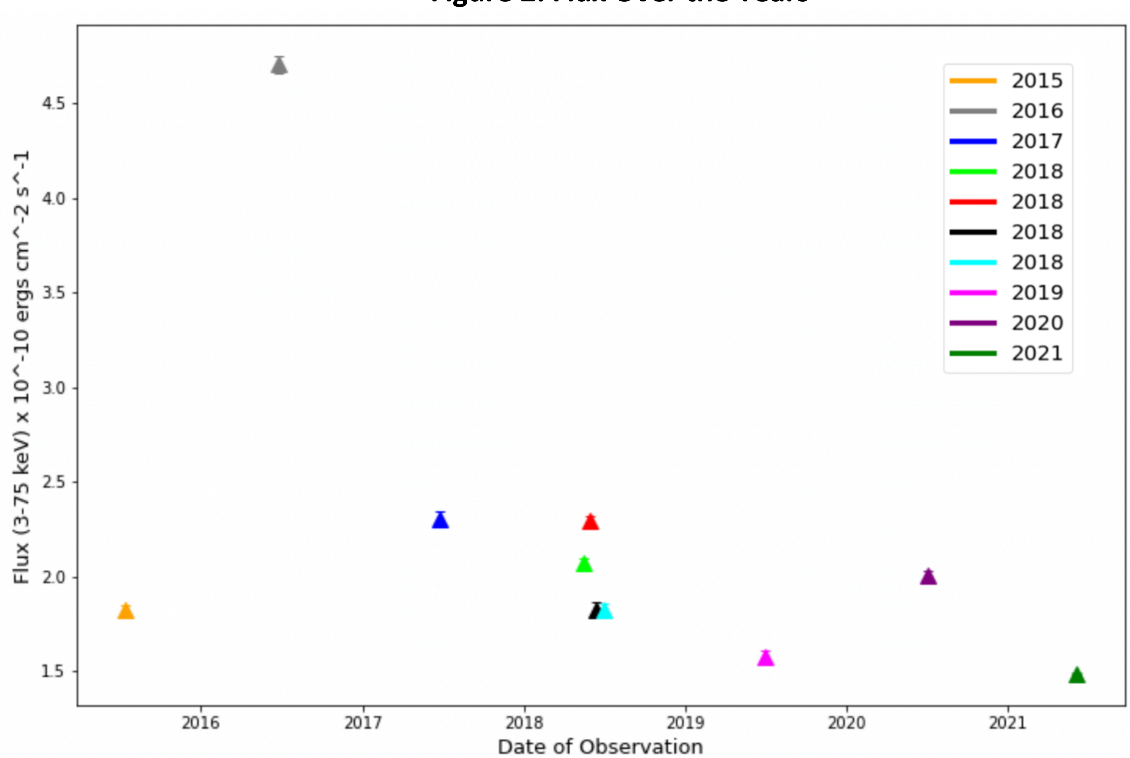
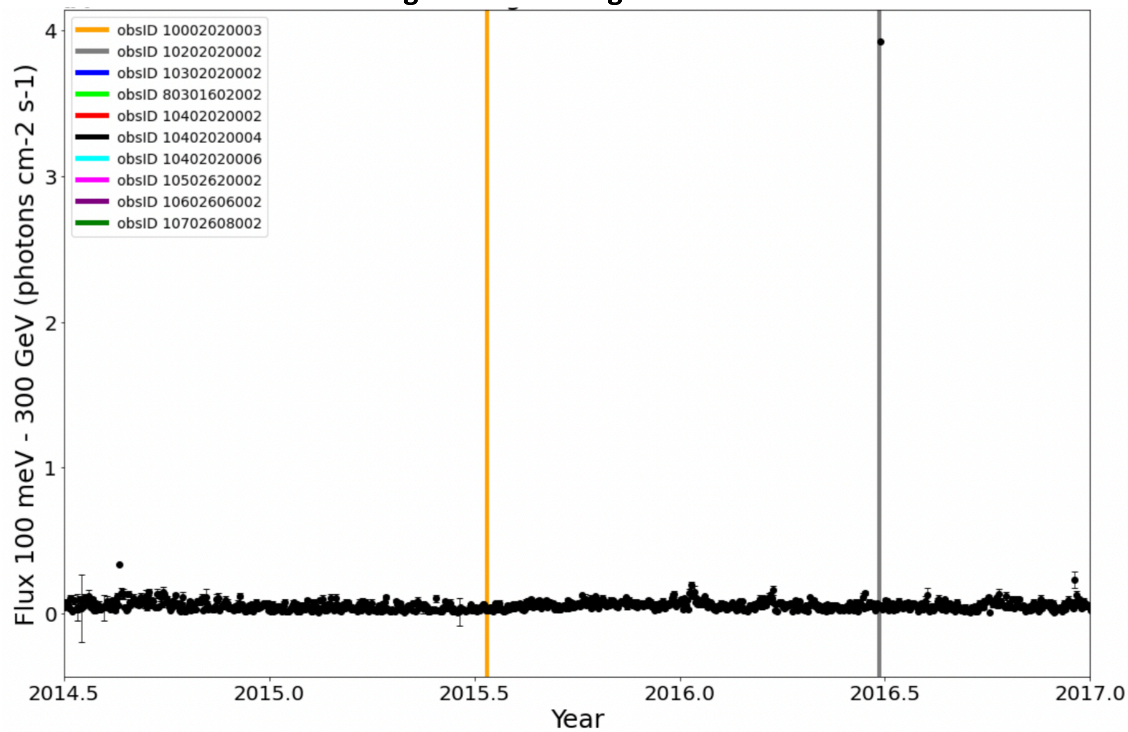
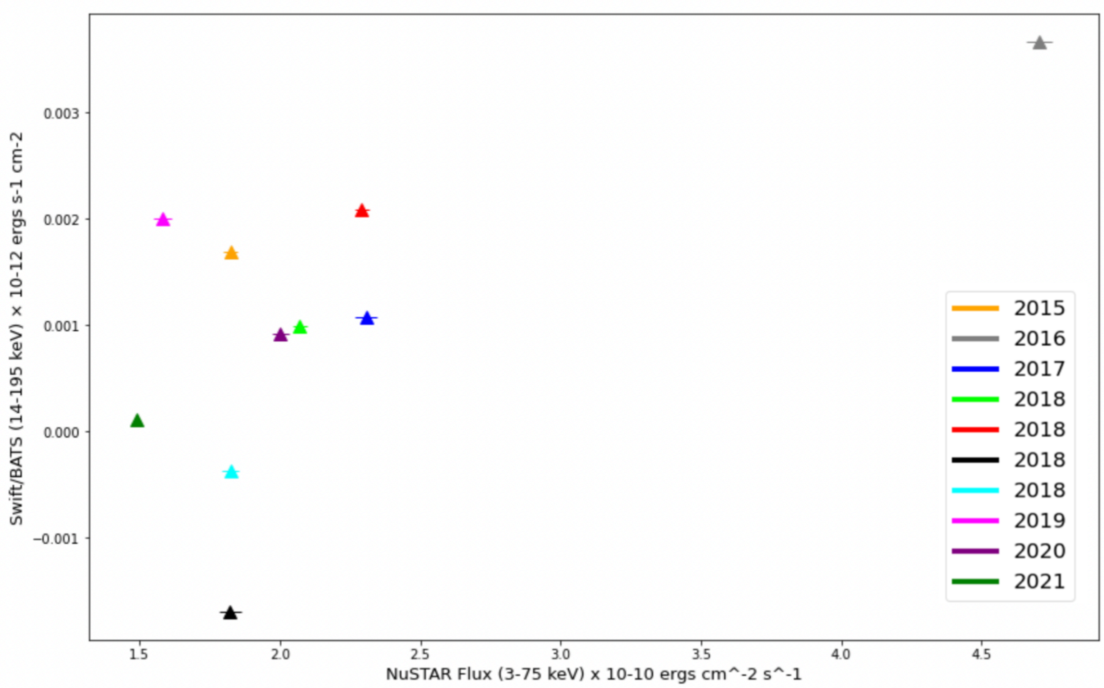


Figure 3: Fermi Lightcurve on 3C273



I plotted the flux in the 3-75 keV band obtained from NuSTAR against the flux obtained from Swift/BATs at the corresponding observation times (Figure 4). Within the Swift/BATs light curve, the flux found from the time of the 2016 NuSTAR observation also displayed the highest flux - again indicating that the jet emission potentially affected the X-ray data.

Figure 4: Flux Comparison Between NuSTAR and Swift/BATS

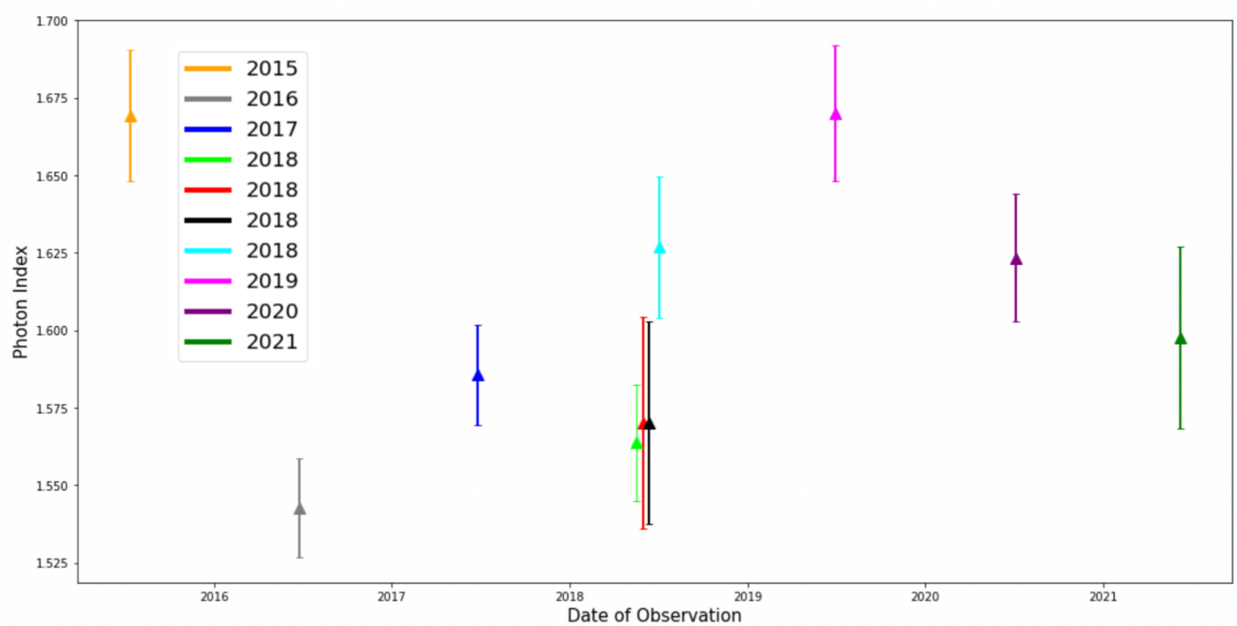


3C273 Over the Years

Photon index

Records on the spectral index of 3C273 spanning the years 1970-2005 presents significant short-term variations as well as a long-term trend. Over the last 50 years, we can see that the source has softened over time. In 1980 the source was at a harder state of almost 1.4 and has since softened to around 1.6[2]. From the 2015-2021 observations presented in Figure 5, the spectral index seems to consistently vary around a value 1.6-1.7 which aligns with the long-term trend. Interestingly, in 2003, the source was in its softest state with a photon index of around 1.8 but has since hardened[2].

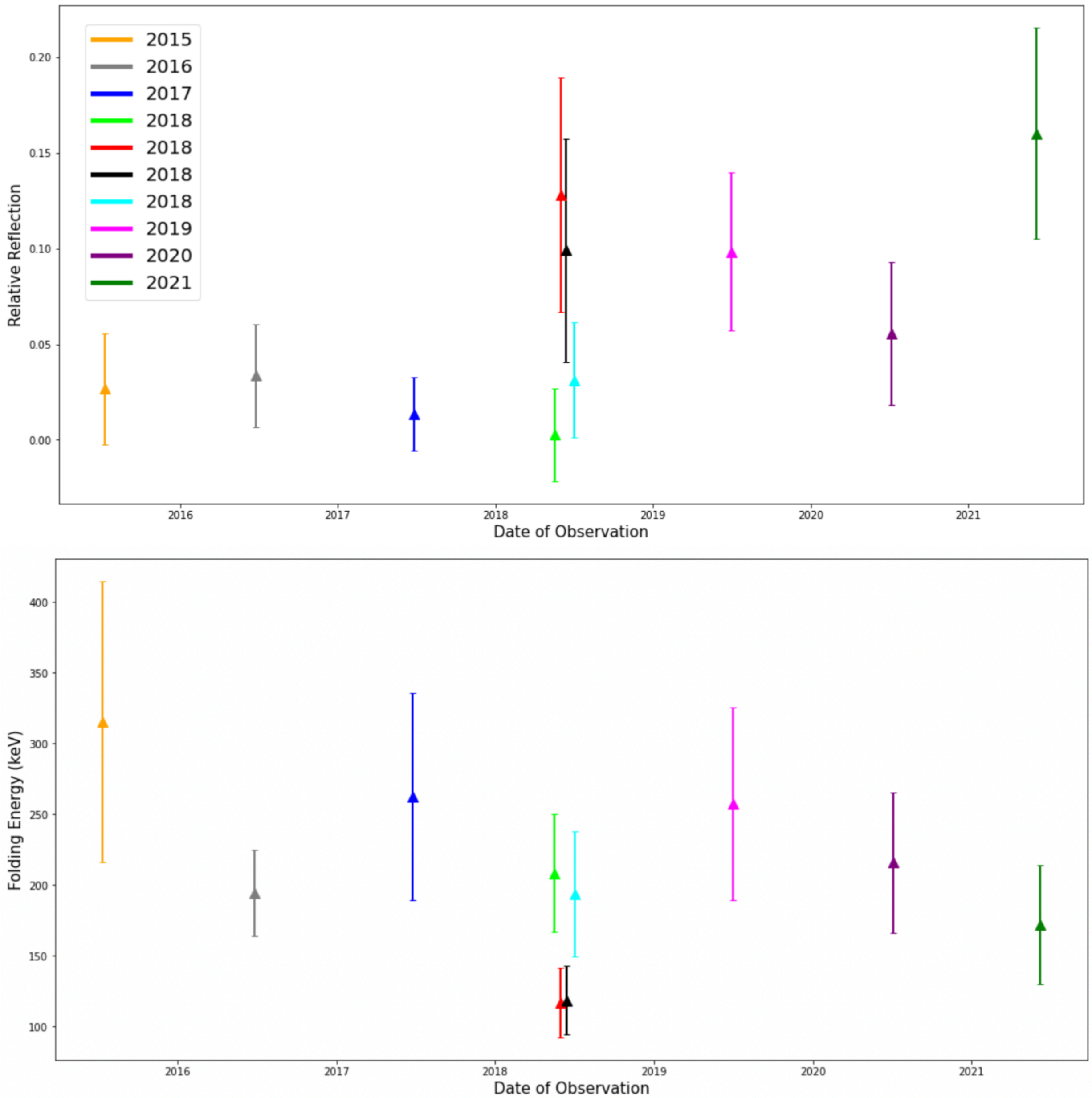
Figure 5: Spectral Index Over the Years



Relative Reflection and Folding Energy

I plotted the folding energy and relative reflection against time for all observations as seen in Figure 6. Short-term variations between the epochs are seen and we generally see a high cutoff energy around 250 keV and a weak relative reflection around .10 (explaining why the iron line isn't visible or very faint). There is an increase or a jump in the relative reflection component in 2018 which is consistent until the 2021 observation.

Figure 6: Relative Reflection and Folding Energy Over the Years

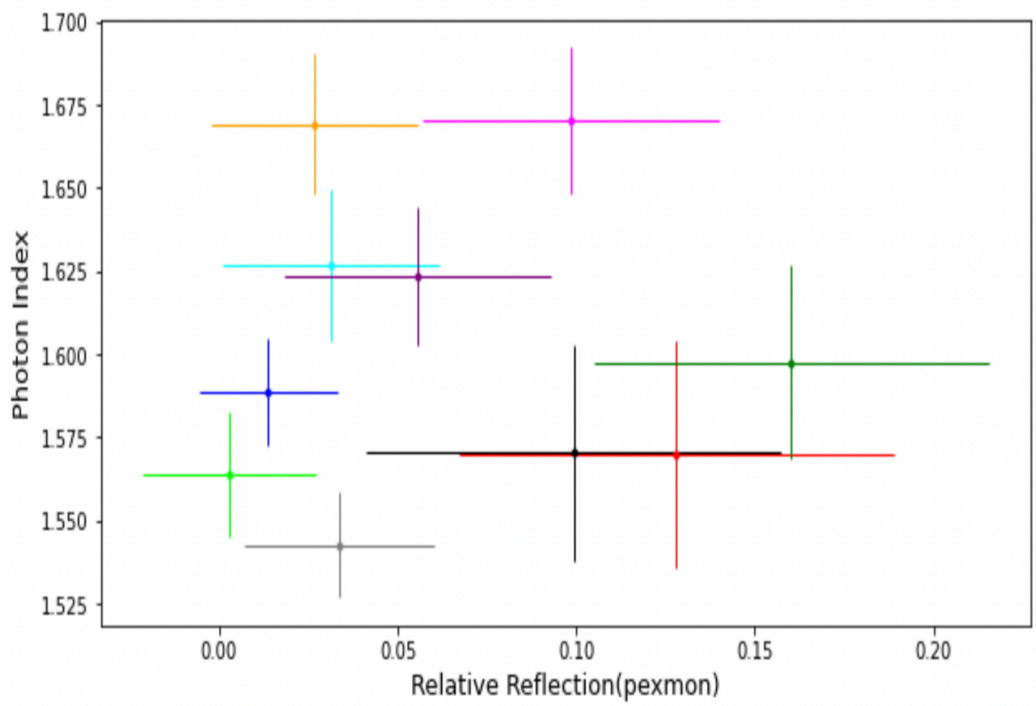


Correlation Studies

Spectral Index

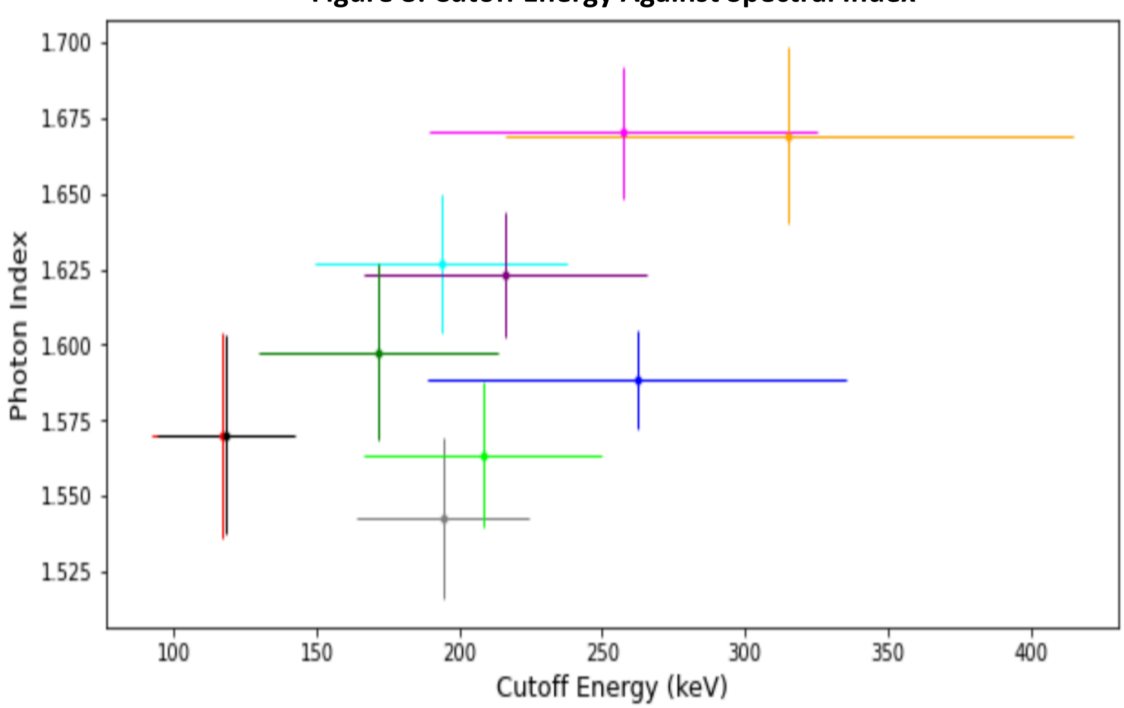
When plotting the relative reflection against the spectral index we obtained a P-value of 0.88 showing there was no correlation between the two components (Figure 7). This is reasonable as the reflection component is very weak - and there is little evidence of an iron line.

Figure 7: Relative Reflection Against Spectral Index



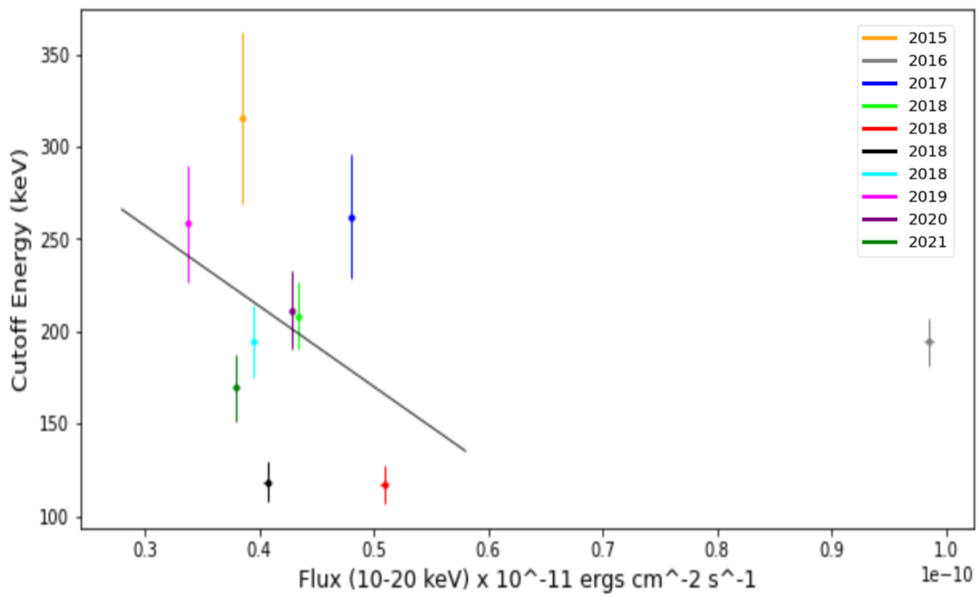
When plotting the cutoff energy against the spectral index, it appears that a lower energy cutoff value indicates a harder spectrum (Figure 8). A correlation test produces a p-value of 0.16 indicating that the correlation is weak.

Figure 8: Cutoff Energy Against Spectral Index



Finally, I looked at the relationship between the photon index and flux as seen in Figure 9. The plot indicates an inverse relationship: the spectrum hardens as the flux increases. This inverse relationship is not common for AGNs, more specifically AGNs without a relativistic jet. Generally, the spectrum softens with increasing flux. However, results from previous studies on 3C273 and a 1999-2000 campaign with RXTE observed an inverse correlation as well[1]. This potentially indicates that the variability is driven by the jet flux. A correlation study resulted in a p-value of .43 so statistically there is no correlation.

Figure 9: Flux Against Spectral Index



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Future Research Directions

Moving forward, it would be interesting to conduct a study on the presence of the iron line in the spectrum of 3C273. Looking at the combined spectrum of 3C273 obtained in my studies, it is unclear whether the iron line is present, as it is very faint. Additionally, we would want to incorporate more data on 3C273 into our studies. Going forward, we would include data on 3C273 from other observatories such as INTEGRAL, Chandra, Suzaku, Swift, and XMM-Newton. This would allow us to study the source in different energy bands.

Methods

I installed the latest version of the HEASoft X-ray data analysis software package as well as the NuSTAR calibration database (CALDB) and downloaded ten NuSTAR observations on 3C273 to be processed from the NuSTAR archive at HEASARC. As a first step, I ran the NuSTAR data analysis pipeline (nupipeline) to obtain level 2 output files that are calibrated, cleaned, and screened events files from the NuSTAR X-ray telescope. Then, I extracted a point source spectrum and light-curve using nuproducts[1]. The detector records the energy and position of X-rays so the corresponding spectrum outputs the Energy (keV) against Normalized counts (s^-1 keV^-1). After processing all observations, I began analyzing each spectrum. Using XSpec, an X-ray spectral-fitting program, I fitted each observation independently to the pexmon model. Each observation contains data from both the NuSTAR detectors (FPMA and FPMB).

Using XSpec, we can obtain parameter values such as the cutoff energy, photon index, relative reflection, and normalizations from the fitted spectra. I then used JupyterLab to produce graphs using the values obtained from XSpec.

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References

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