Long-term X-ray variability of the NLS1 Ark 564

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Abstract

We present a systematic long-term X-ray spectral analysis of the Narrow-Line Seyfert 1 galaxy Ark 564 using sixteen years of *Swift*/XRT observations. Significant variability is observed in both the soft (0.3-2 keV) and hard (2-10 keV) bands, with a strong positive correlation between them, indicating a close connection between the emission components of the accretion flow–corona system. Spectral modelling reveals a prominent soft excess that cannot be adequately described by an absorbed power law. A warm Comptonization model provides statistically improved fits, supporting an origin of the soft excess in a warm, optically thick corona. We also applied a relativistic reflection model to representative observations; however, given the moderate spectral resolution and limited high-energy coverage of *Swift*/XRT, the current data do not allow us to robustly determine whether reflection provides a superior or physically preferred description. Our results indicate that warm Comptonization offers a consistent explanation for the observed soft excess in Ark 564 within the limitations of the available data, while deeper broadband observations are required to definitively distinguish between competing models and comprehensively characterise the long-term X-ray spectral variability of the source.

Introduction

Active Galactic Nuclei (AGN) are extremely luminous regions at galactic centres powered by accretion onto supermassive black holes. Narrow-Line Seyfert 1 (NLS1) galaxies are a distinct AGN subclass characterised by rapid X-ray variability, relatively low black-hole masses and high accretion rates. Their X-ray emission is thought to arise primarily from inverse Compton scattering of disc photons by a hot corona located close to the black hole. A prominent feature in many NLS1 galaxies is the soft X-ray excess, whose origin remains an important question in AGN studies. Warm Comptonization, in which disc photons are upscattered by a warm, optically thick corona, has been proposed as a physical mechanism for producing the soft excess in AGN [1–4].

Ark 564 is an X-ray-bright NLS1 galaxy with a relatively low black-hole mass and a high accretion rate. Its strong variability makes it an excellent laboratory for studying the connection between the accretion disc and X-ray corona. This work investigates the long-term X-ray spectral and flux variability of Ark 564 using Swift-XRT observations.

Main Objectives

1. How strongly does Ark 564 vary in the X-ray band over long timescales?
2. What are the physical properties of the Comptonizing corona?
3. What is the origin of the observed soft X-ray excess in the source?
4. How does the X-ray spectral shape vary with $L_{0.3-10\,\mathrm{keV}}/L_{\mathrm{Edd}}$?

Data Reduction Methods

Ark 564 has been monitored by *Swift* since 2005. We retrieved 99 observations from the X-ray Telescope [XRT] onboard *Swift* covering the 0.3–10 keV energy range between 2005 and 2021, of which 85 were suitable for spectral analysis. Data reduction and analysis were performed using HEASOFT v6.31.1. Level-2 data products for the XRT observations were derived from Level-1 data using the standard processing pipeline *XRTPipeline* version 0.13.7, and calibration was performed using CALDB version 20240522. Level-2 event files and source/background spectra were generated following the standard XRT reduction procedure. The spectra were grouped to a minimum of 20 counts per bin and fitted in XSPEC using χ^2 statistics.

Spectral Analysis

We fitted the Swift-XRT spectra using progressively more physical models. The Galactic absorption was described using `tbabs`, with $N_{\mathrm{H}} = 4.98 \times 10^{20}$ cm^{-2} fixed at the Galactic value.

To phenomenologically describe the soft excess, we first used `tbabs*(bbody+powerlaw)`:

$$F_1(E) = e^{-N_{\mathrm{H}}\sigma(E)} \left[F_{\mathrm{bb}}(E) + K_{\mathrm{p}} E^{-\Gamma} \right], \tag{1}$$

where $F_{\mathrm{bb}}(E)$ represents the blackbody component, with its temperature fixed at $kT = 0.1$ keV, and $K_{\mathrm{p}}E^{-\Gamma}$ represents the primary power-law continuum.

A physically motivated description was then obtained using `tbabs*Simpl*NthComp`:

$$F_2(E) = e^{-N_{\mathrm{H}}\sigma(E)} \left[(1 - f_{\mathrm{sc}}) F_{\mathrm{nthComp}}(E) + f_{\mathrm{sc}} P(E) \right], \tag{2}$$

where $F_{\mathrm{nthComp}}(E)$ represents the thermal Comptonization spectrum produced by the warm corona, f_{sc} is the scattering fraction, and $P(E)$ is the power-law tail generated by the convolution model `Simpl` [5], which scatters a fraction of the `NthComp` [6, 7] seed photons. For `NthComp`, the seed-photon temperature was fixed at $kT_{\mathrm{seed}} = 0.01$ keV and `UpScOnly`=1.

Relativistic reflection was also tested for the highest and lowest-flux observations using `tbabs*relxillCp`, with `relxillCp` [8] modelling reflection from an ionized accretion disk. This allowed us to assess whether reflection could provide an alternative explanation for the observed soft excess.

The unabsorbed fluxes were calculated using the `cflux` convolution model, and luminosities were obtained from $L = 4\pi D^2 F$, adopting $D = 98.5$ Mpc. Long-term variability was quantified using the fractional variability amplitude, F_{var}, while Pearson and Spearman correlation tests were used to investigate relationships between the soft and hard X-ray fluxes and spectral parameters.

Results

- Soft X-ray excess: All 85 Swift/XRT spectra show a prominent soft X-ray excess below ∼2 keV. The absorbed power-law model adequately describes the hard continuum but leaves systematic soft-band residuals. Adding a blackbody improves the fits, but provides only a phenomenological description.
- Warm-corona interpretation: The `tbabs*Simpl*NthComp` model provides statistically improved and physically motivated fits across the observations. The warm corona has electron temperatures of $\sim$ 0.1-0.3 keV, while the primary photon index varies over $\Gamma \sim$ 1.3-2.8.
- Long-term variability: Strong intrinsic variability is observed throughout the monitoring period. The fractional variability amplitudes are $F_{\mathrm{var}} = 0.30 \pm 0.01$, 0.31 ± 0.09, and 0.19 ± 0.04 in the 0.3–10, 0.3–2, and 2–10 keV bands, respectively, showing stronger variability in the soft X-ray band.
- Flux correlations: The soft and hard X-ray fluxes are strongly correlated ($r = 0.75$, $p = 1.84 \times 10^{-11}$), indicating coherent broadband variability and suggesting a common underlying physical driver.
- Accretion rate: The mean 0.3-10 keV luminosity is $\sim 8.8 \times 10^{43}$ erg s^{-1}, corresponding to an X-ray Eddington ratio of $\langle \lambda_{\mathrm{Edd}} \rangle \approx 0.27$.
- Reflection: `relxillCp` was tested for representative high and low-flux observations. Although it provided acceptable fits, the ionization parameter and reflection fraction remain poorly constrained, preventing a firm identification of reflection as the dominant origin of the soft excess.

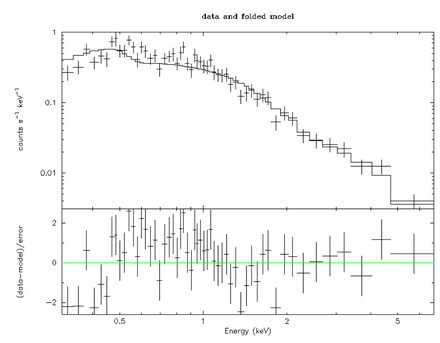


Figure 1: Spectral fits in the 0.3-10 keV band for the observation 00081687001 of Ark 564 using the model `tbabs*(bbody+powerlaw)`.

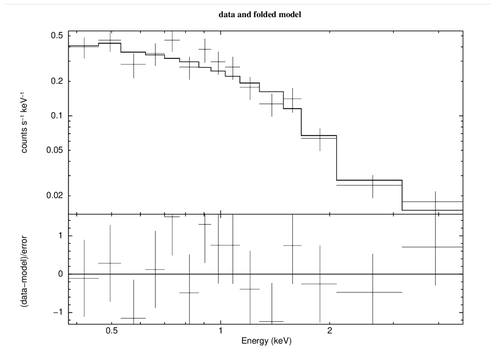


Figure 2: Spectral fits in the 0.3-10 keV band for the observation 00092237011 using the model `tbabs*relxillCp`.

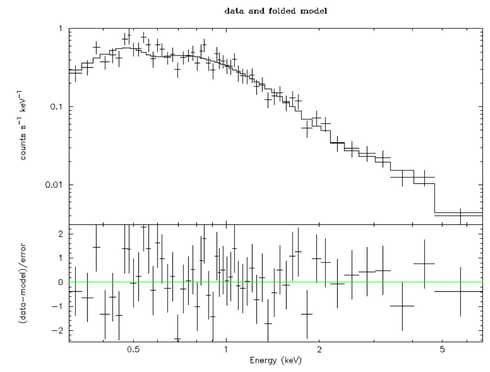


Figure 3: Spectral fits in the 0.3-10 keV band for the observation 00081687001 of Ark 564 using `tbabs*Simpl*NthComp` model. The top panel shows the unfolded spectrum and the bottom panel shows the data-to-model residuals.

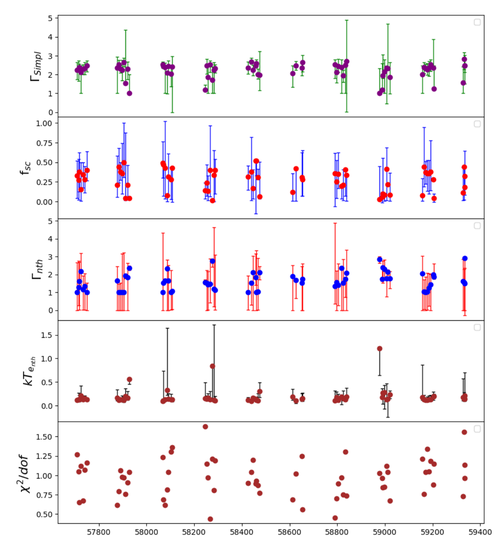


Figure 4: Temporal evolution of spectral parameters as a function of MJD obtained from the model `tbabs*Simpl*NthComp`.

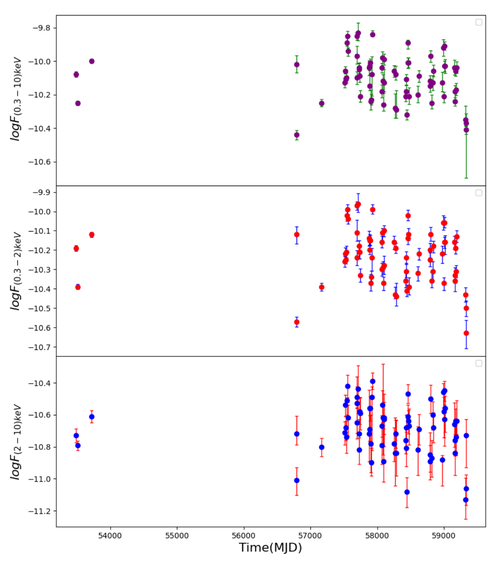


Figure 5: Variation of logarithmic flux values of `tbabs*Simpl*NthComp`.

Conclusions

- The long-term Swift/XRT observations reveal persistent soft X-ray excess and strong intrinsic variability in Ark 564.
- The warm-corona model provides the most consistent physical interpretation, with a warm, optically thick corona producing the soft excess through Comptonization of disk photons, while a fraction of this emission is upscattered by a hot, optically thin corona to form the hard X-ray power law.
- The stronger soft-band variability and strong soft–hard flux correlation indicate that the warm and hot coronal components are closely connected and respond to changes in the inner accretion flow.
- The substantial variability in the scattering fraction suggests changes in the geometry of the X-ray emitting region over the monitoring period.
- Reflection cannot be ruled out, but the available Swift/XRT data do not require it. Broadband observations extending to ∼50–80 keV, are required to disentangle warm-corona and reflection contributions.

Overall, the results support a variable, high-accretion-rate disk–corona system in which warm Comptonization plays a major role in producing the soft X-ray excess of Ark 564.

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