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The optical and X-ray properties of a sample of Seyfert galaxies that have undergone significant spectral change

Daymore T.M. Makope*
Department of Physics, University of Johannesburg
P.O. Box 524, Auckland Park 2006, Johannesburg, South Africa
E-mail: 201517415@student.uj.ac.za

Hartmut Winkler
Department of Physics, University of Johannesburg
P.O. Box 524, Auckland Park 2006, Johannesburg, South Africa
E-mail: hwinkler@uj.ac.za

Francois van Wyk
Department of Physics, University of Johannesburg
P.O. Box 524, Auckland Park 2006, Johannesburg, South Africa
E-mail: fvw@saao.ac.za

This paper presents the initial findings of a study of the optical spectra of two sets of data for about 50 Seyfert galaxies taken 20 years apart. We compared the spectra for the different epochs and identify some objects where significant spectral changes occurred. We describe the nature of the spectral changes and collate available information about the X-ray properties of these AGN. In particular, we probe whether the degree of spectral variability, which may range from relatively steady to "changing look" AGN, correlates with any X-ray features. We attempt to interpret our findings in terms of possible physical models of these AGN.

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*Speaker.

1. Introduction

Active galactic nuclei (AGN) are spiral galaxies with extremely bright nuclei. A massive black hole at the nucleus of the galaxy is believed to power these galaxies, fed by accretion discs of gas from its surrounding environment. Seyfert galaxies are a subclass of AGN which have nuclei with luminosities ranging between 10^8 and 10^{11} solar luminosities. They have visible and infrared spectra that show very bright emission lines of hydrogen, helium, nitrogen and oxygen exhibiting strong Doppler broadening, which implies velocities from $500\,\mathrm{km\,s^{-1}}$ to sometimes over $10000\,\mathrm{km\,s^{-1}}$ [1].

These objects are known to show continuum and emission line intensity variations [2], including emission profile variations on timescales of as short as a few weeks to as long as several years, with most changes observed in the broad line region. The unification model for AGN [3] [4] interprets the variation in AGN properties as arising from different viewing angles to the centres of such sources and from a large amount of obscuration along the line of sight. It says that broad emission profiles are observed when the nucleus of the galaxy is unobscured and are absent or weak when the nucleus of the galaxy is viewed along a line of sight obscured by a dust torus.

Changing look active galactic nuclei (CL AGN) are a class of AGN that undergo drastic changes in their spectral properties in the optical region and/or in the X-ray region [5]. They can change their spectral type within time periods that range from days to decades. This presents a challenge to the unification model, as the dusty torus should not change its characteristics over short time intervals. These changes can be variations in the shape of spectral profiles, changes in the intensity of the lines and disappearance/appearance of (broad) emission lines together with dramatic continuum flux changes that are orders of magnitude larger than those expected from typical AGN variability. These variations provide information on the structure and kinematics of the regions producing the emission line.

More than 40 years of monitoring of the AGN in Mrk 590 showed that the activity of the nucleus has diminished significantly, accompanied by the complete disappearance of the broad Balmer profiles in 2014 [6]. Long-term monitoring of the galaxy NGC 3516 [7] showed an increase followed by a complete disappearance of the broad Balmer lines from a spectrum recorded in 1997 to one obtained in 2018. It was concluded that the absorbed broad emission lines indicate possible obscuration of the broad line region. NGC 1566 was observed with nearly undetectable broad components between the 1970s and 1980s [8] but a recent study [9] shows that the object experienced a dramatic outburst in all wavelengths with Hβ becoming a lot stronger than [OIII]λ5007Å. The paper proposed tidal star stripping as a possible cause of the outburst.

A few mechanisms have been proposed to explain the observed drastic changes, including:

1. changes in the accretion rate [10] of mass onto the supermassive black hole – depletion of nuclear material results in objects evolving from high accretion rate to low accretion rate, which changes the structure of the broad line;
2. variable obscuration [11] of the nuclei due to increased acceleration outflow and the presence of a patchy distribution of dust clouds which results in short-lived drastic changes; and
3. a tidal disruption event [12] which occurs when a star passes close to a black hole and gets captured and ripped to pieces due to the tidal forces of the massive black hole, resulting in flares of electromagnetic radiation being observed.

Object name	RA(2000)	Dec(2000)	Date of 1st observation	Date of re-observation
CTS A03.01	20:06:57.9	−32:34:55	06 Oct 1997	07 Jun 2019
1E 2124–14	21:27:32.4	−14:46:48	06 Oct 1997	04 Jul 2019
CTS A08.12	21:32:02.1	−33:42:54	23 May 1999	26 Jul 2019
CTS A09.25	22:07:44.7	−32:34:56	23 May 1999	07 Jun 2019

The main objectives of this study are to observe and characterize the changes to the optical spectra that occurred in a sample of Seyfert galaxies reobserved after a period of 20 years and to use these findings to test physical models of AGN and to highlight possible examples of a sub-class referred to as "changing look AGN".

In this paper, we present preliminary results of four of the objects analyzed to date and report the observed spectral changes for each of these objects.

2. Data sample

The four objects with the analysis results presented in this paper are listed in the table above.

2.1 Observations

The spectra used in this study were obtained using the 1.9 m telescope at the South African Astronomical Observatory in Sutherland, and the data were obtained 20 years apart. The first set of observations come from the period 1997-1999, and the second set of observations spanned the period from 2017 to September 2019. The telescope uses a recently improved Cassegrain spectrograph that offers efficient low- to medium-resolution spectroscopy. The low resolution grating used covered a total overall wavelength range from 3300Å to around 8500Å. A slit width of 2.7 arcsec was used throughout.

2.2 Data reduction and analysis

Flatfields were obtained each night before observing and were later used to correct for pixel-to-pixel sensitivity variations in the spectrum observed that night. Bias frames and arc spectra were also collected, and standard stars were observed a few times during each night. Bias frames were used in removing bias signals during calibration, arc spectra were used to calibrate the spectra for wavelength and spectrophotometric standard star images were used as scaling factors for flux calibration. Blemishes caused by cosmic rays were removed interactively.

Spectral analysis was done in the wavelength range 3500Å to 7500Å after redshift-correction of each spectrum. Spectral line profiles were fitted using the Gaussian function

$$G(x) = a \times \exp[-(x - x_0)^2/2c^2] \tag{2.1}$$

where a is the height of the peak, c is the width of the peak and x and x_0 are the rest and observed x-position of the peak. Figure 1 below shows the measured spectrum and the sum of the fitted Gaussian profiles for the object CTS A09.25 obtained on 23 May 1999. From the parameters a and c, the FWHM (full-width-at-half-maximum) and intensity of the peaks were calculated. The narrow line region is assumed to be constant over intervals of tens of years [3] as the narrow-line region is expected to be several light years in diameter [13]. Therefore, we use the [OIII]λ5007Å line profile for scaling the spectra from the two epochs for comparison by assuming that the intensity of the [OIII]λ5007Å is the same for both spectra. The Balmer decrement – which is the Hα/Hβ line flux ratio – is calculated for each object. The luminosities of the narrow and broad line regions were measured from the fluxes of the [OIII]λ5007Å and Hβ lines, respectively [14]. These findings will be used to test physical models of AGN and to highlight possible examples of new CL AGN cases.

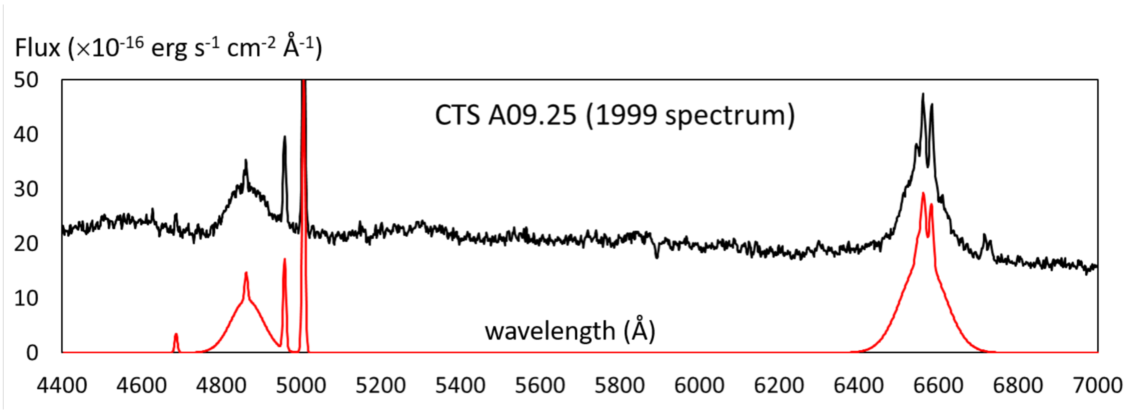

Figure 1: Measured (black) and model line emission spectrum (red) for CTS A09.25 (23 May 1999). The model only utilised the Balmer, HeII, [OIII] and [NII] emission lines.

3. Results

Results for each individual object are presented in the subsections that follow.

3.1 1E 2124–14

In 1997, the spectrum showed strong Balmer emission lines with line intensity ratio [OIII]λ 5007Å to Hβ of 0.543. Hβ and Hα line strengths can be used to classify Seyfert galaxies. The spectrum from 2019 can be classified as a Type 1.9 Seyfert galaxy. The Balmer line strengths have decreased significantly, with only a weak broad component of the Hα line remaining, as shown in Figure 2. The strength of the line is now comparable to [OIII]λ5007Å and it now shows a visible [NII]λ6583Å line which was hidden in the Hα profile in 1997. The once strong and broad Hβ profile has completely vanished suggesting a new changing look case for 1E 2124–14. As implied by its name, this AGN was a bright X-ray source at the time of its discovery in the early 1980's, with an *Einstein Observatory* 0.3-3.4 keV band measurement of 2.53×10^{-13} erg cm^{-2} s^{-1} [15]. The target does not feature in subsequent lists of X-ray bright sources, which would be consistent with the overall fading of this AGN during the last few decades.

3.2 CTS A08.12

The 2019 spectrum in Fig. 2 below shows similar continuum and Balmer line strengths relative to the forbidden lines, but the profiles of Hβ and Hα have changed substantially. Furthermore, the broad HeIIλ4686Å emission clearly visible in the earlier spectrum has almost vanished completely, and HeIλ5876Å has faded. ROSAT measured a 0.3-3.4 keV flux of 3.31×10^{-11} erg cm^{-2} s^{-1} in the 1990's [16]. Data from the Swift archive shows that the X-ray flux in the 0.3-10 keV band for the object decreased from 7.5×10^{-11} erg cm^{-2} s^{-1} in July 2007 to 1.44×10^{-11} erg cm^{-2} s^{-1} in March 2013, which are both in the same order of magnitude range as the earlier ROSAT flux.

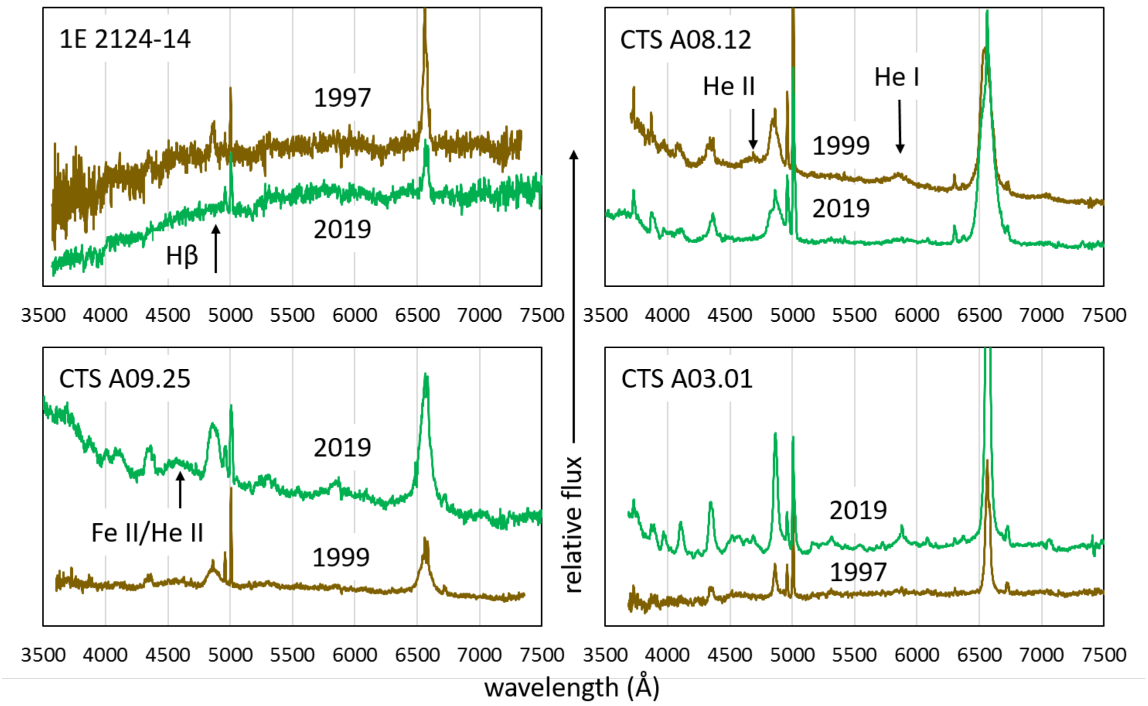

Figure 2: Spectra for 1E 2124–14, CTS A08.12, CTS A09.25 and CTS A03.01 for the years 1997/1999 (in brown) and 2019 (in green). The spectra were scaled vertically so that the forbidden lines are of similar strength in both spectra. For 1E 2124–14 and CTS A08.12 the earlier spectrum was also displaced upward slightly to avoid overlapping of the continua. Note the complete disappearance of Hβ in 1E 2124–14.

3.3 CTS A09.25

Unlike CTS A08.12, CTS A09.25 shows a strengthening of the Balmer lines. Their peaks were weaker than the [OIII]λ5007Å line in the first epoch. The Balmer lines from the 1999 spectrum show well defined narrow components. However, in 2019, all the Balmer lines became much stronger than before. Hα has become the dominant line in the spectrum with the [NII]λ6548Å line blended with the strong Hα blue wing. The Hα and Hγ lines maintain their structures with the distinct nearby forbidden line peaks. The Hβ profile changed substantially over the 20 years, showing strong wings in the new spectra which extend under the [OIII] doublet. There is an increase in the strength near the HeIIλ4686Å line which could also be due to the blending by FeII lines in the region. Swift data shows X-ray flux in the 0.3-10 keV band to be 5.0×10^{-11} erg cm^{-2} s^{-1} in July 2008 and 4.1×10^{-11} erg cm^{-2} s^{-1} in October 2012. This appears to be broadly consistent with the earlier measured ROSAT 0.3-3.4 keV flux of 1.27×10^{-11} erg cm^{-2} s^{-1} [16].

3.4 CTS A03.01

CTS A03.01 shows an increase in the overall continuum intensity accompanied by strengthening of the broad Balmer lines. The object still maintains its classification as a narrow-line Seyfert 1 galaxy [17]. The intensity of Hβ and Hα increased significantly with noticeable broadening. Mahony et al. [16] reported an X-ray flux on 2 Oct 1994 of 9.03×10^{-12} erg cm^{-2} s^{-1} in the 0.1 - 2.4 keV band.

4. Conclusion

In this paper, we have reported on the initial results of four objects which have undergone spectroscopic changes over 20 years. The observed change in the Hα line of CTS A08.12 is similar to the one observed for NGC 4151 between 1996 and 2004. We find both the X-ray and optical emission to be variable for CTS A08.12 and CTS A09.25, with the amplitude of the optical emission smaller than that of the X-rays. The strengthening of the Balmer lines for CTS A03.01 is the common case which might be explained by the unified model. We note that 1E 2124–14 is a possible new changing look case with a glaring disappearance of the once strong Balmer lines, and that historical X-ray flux measurements are consistent with that. More analysis is needed to confirm this.

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