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1E 0502–667: An AGN without narrow lines?

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1E 0502–667 is a comparatively nearby Seyfert 1 galaxy discovered 40 years ago during follow-up observations of X-ray sources in the direction of the Large Magellanic Cloud. Despite its early identification as an AGN, only a few studies have been carried out of this target since then. We obtained a spectrum covering its entire optical range in 2019. This confirmed the presence of broad lines in the spectrum but also highlighted that the narrow line system in this AGN is one of the weakest ever identified for objects in this luminosity range. We present our profile fits and associated measurements of the spectral lines. The unusual spectrum also prompted us to analyse a decade-long set of brightness measurements from the ASAS-SN project and to obtain a series of observations during the last year with the Las Cumbres robotic telescope network. We present the results of our investigation of the spectroscopic and photometric data, which we here attempt to interpret with the aid of measurements available from other wavelength regimes (X-ray, infrared, radio).

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1. Introduction

An early 1980's programme to identify X-ray sources in the direction of the Large Magellanic Cloud (LMC) [1] identified the source 1E 0502–667 with a background active galactic nucleus (AGN) after a spectrum showed this to be a Seyfert galaxy with a redshift of $z = 0.64$. While the discovery paper does not display the spectrum or present other related measurements, it describes the spectrum as containing "very broad" Balmer lines and "strong Fe II" emission.

In the years that followed its discovery, 1E 0502–667 has received comparatively little attention. The AGN is identified in some radio, infrared, ultraviolet and further X-ray surveys, but no further optical data has ever been published. We therefore sought to obtain a better quality optical spectrum of 1E 0502–667 to test the previous classification, determine the level of activity and estimate physical properties that can be extracted from this.

2. Data collection

We secured an optical spectrum of 1E 0502–667 covering the wavelength range 3500-8000 Å on 31 March 2019 using the SpUpNIC spectrograph [2] on the 1.9 m telescope at the South African Astronomical Observatory's Sutherland station. The slit width was set to 2.7 arcsec and the total integration time was 2400 s. Wavelength calibration was achieved through the recording of argon lamp spectra before and after each integration. The wavelength-pixel position relation was determined by a third-order polynomial that results in a wavelength determination of better than 1 Å throughout the optical range. Bias and flatfield frames were generated at the start of the night. The flux was calibrated through an observation of the spectrophotometric standard star LTT 4816 [3] soon after the AGN. The spectral reduction was carried out using a slightly modified interactive version of the routine SAAO reduction pipeline, which incorporates standard processing such as cosmic ray removal. The modified package also allowed the interactive removal of telluric absorption bands and spectral blemishes missed by the automated spectral reduction routines. The redshift was determined by cross-correlating the spectrum with an AGN template [4]. The calibrated rest-frame spectrum is displayed in Fig. 1.

In order to explore the long-term variability of 1E 0502–667, we compiled all the available photometric measurements collected by the All-Sky Automated Survey for Supernovae (ASAS-SN) [5, 6]. These provide us with a set of over 5000 brightness measurements spanning the nine-year period 2014-2022. As the uncertainties in individual photometric measurements from these instruments are usually quite high (~ 0.3 mag), and as optical variations in Seyfert galaxies typically have time scales of the order of a month, we binned the photometry into 10-day intervals, and the representative magnitude for each 10-day interval was then determined to be the median of all magnitudes measured during that time. The photometric measurements were initially made with a V-filter, but the ASAS-SN programme gradually replaced these with a g-filter around five years ago. There was a 12-month period from Oct 2017 to Sep 2018 when photometric data is available in both filters. Comparing the V and g magnitudes during this period of overlap allowed us to determine the offset between these, and to thereafter convert all magnitudes obtained with the g-filter to V-magnitudes. The aperture corresponds to a radius of 16 arcsec.

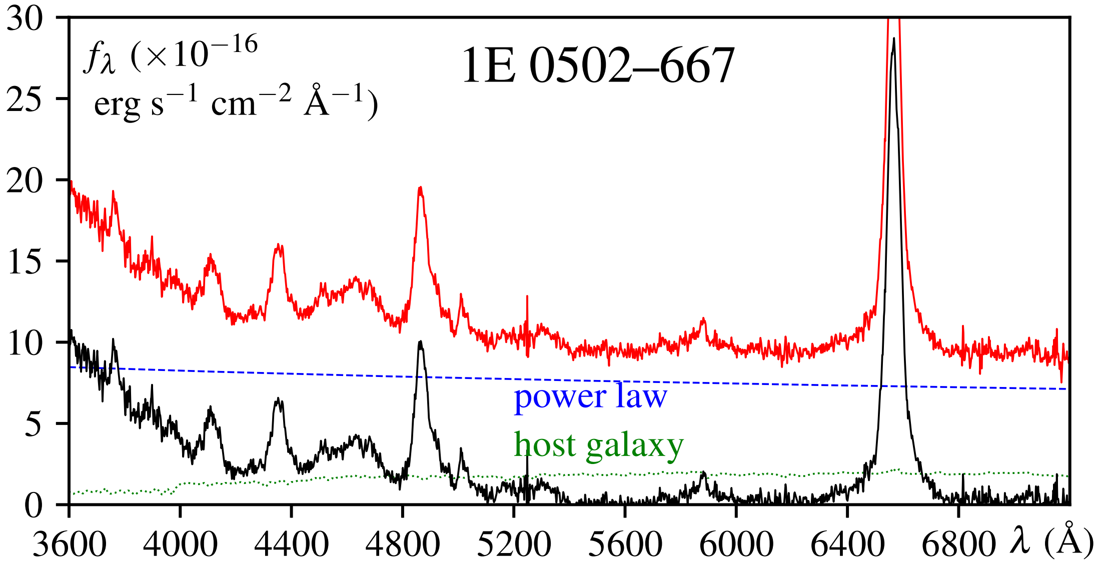

Figure 1: Rest frame optical spectrum of 1E 0502–667 observed on 31 March 2019 with the SAAO 1.9 m telescope, corrected for interstellar reddening. The plot also shows the estimated host galaxy and power law component contributions (see Section 3) and the residual spectrum when these are subtracted.

We also carried out BVu′g′r′ photometric observations of 1E 0502–667 using the SAAO, Cerro Tololo and Siding Spring 1.0 m telescopes of the Las Cumbres Observatory Global Telescope Network (LCOGT) [7]. These telescopes are equipped with Sinistro cameras and produce images of 26 × 26 arcmin. Integration times per frame were 30 s and 40 s for the Landoldt V and B filters respectively, and 240 s, 30 s and 20 s for the SDSS u′, g′ and r′ filters respectively. These integrations were always repeated one more time to identify any potential contamination of the measurements due to unnoticed cosmic rays or other effects. Seventeen photometric data sets were secured between Feb 2021 and Nov 2022 with a cadence of roughly 1-month when possible. The frame reductions (bias and dark frame subtraction, flat field correction, removal of cosmic rays and source extraction) are performed by the LCOGT's BANZAI pipeline. The photometric zero points were determined through reference magnitudes for comparison stars on the frame obtained from the AAVSO Photometric All-Sky Survey (APASS).

The data processing described in this paper made use of Astropy:[1] a community-developed core Python package and an ecosystem of tools and resources for astronomy [8].

3. Spectroscopic results

The spectrum of 1E 0502–667 displayed in Fig. 1 is remarkable primarily for the weakness if not absence of the narrow forbidden lines typically associated with Seyfert galaxies, such as the [O III] 4959,5007Å doublet. Such characteristics are normally only seen in distant, much more luminous quasars. We investigate this peculiarity further through a more in-depth spectral analysis.

[1]http://www.astropy.org

The spectrum was first corrected for foreground extinction in our Galaxy by applying a Fitzpatrick reddening law [9] with $R_V = 3.1$ and a reddening value of $E(B - V) = 0.066$ determined with the NED calculator based of the maps of Schlafly and Finkbeiner [10].

For the host galaxy spectrum we adopted the Sb galaxy template of the Kinney-Calzetti atlas [11]. We approximated the AGN continuum by means of a power law $f \propto \lambda^{-p}$, obtaining an optimal fit with a power law index $p = 0.25$.

Subtracting the host galaxy and power law components from the measured spectrum yields the emission line spectrum of 1E 0502–667 that is also displayed at the bottom of Fig. 1. We measure the redshift to be $z = 0.0635$. We note the following about this spectrum:

- There is a blue excess that is very prominent below 4000 Å, and is present to a lesser degree up to about 5000 Å. This suggests the presence of what is referred to as a 'blue bump', which is associated either with an additional very hot thermal component, or might be due to blended lower order Balmer lines and the related Balmer continuum.
- The broad line of Hα extends towards the blue as far as $\sim$ 6300 Å, which equates to a maximal gas speed of $\sim$ 15000 km s^{-1}.
- while emission line features near 3750 Å and 5000 Å might initially appear like the [O II] 3727 Å and [O III] 5007 Å lines that are usually prominent in Seyfert galaxies, an inspection of the wavelength associated with these peaks shows these to be inconsistent with the required wavelengths. They are most likely a blend of Fe II lines at $\sim$ 3750 Å and Fe II 5018 Å.
- the enhancement to the red of the Hγ peak position is likely to be Fe II rather than [O III] 4363 Å.
- the narrow spike near 5200 Å is a blemish associated with the imperfect sky line subtraction. So no narrow lines are immediately distinguishable in the spectrum.

We then tested whether there was evidence of (i) the [O III] 4959,5007 Å doublet in the red wing of Hβ and (ii) the [N II] 6548,6583 Å doublet that is typically strong in AGN, but blends with Hα. We indeed do find that the better fits to the Hβ and Hα profiles are possible when we combine a Balmer line profile of two Gaussian components (with the broader of these two shifted slightly towards the red) with very weak, narrow Gaussians corresponding to the positions of the above-mentioned forbidden lines.

4. Photometric results

The ASAS-SN light curve covering most of the period 2014-2022 is displayed in Fig. 2. We note that the luminosity of the AGN has not varied dramatically over this period. The standard deviation of the points plotted here is 0.12 mJy, which corresponds to about 7% of the average 16 arcsec aperture radius V-flux of 1.70 mJy. The light curve also confirms that when the spectrum was collected, the AGN luminosity was on a scale typical for the last decade, meaning that the spectrum shown earlier appears to be representative of how this looks at most times.

The photometry with LCOGT showed the AGN slowly varying, with $V \sim 16.0$ in Feb 2021, fading slightly to $V \sim 16.2$, then brightening again to $V \sim 16.0$ in early 2022 before fading to $V \sim 16.4$ by Nov 2022. The brightness changes have been plotted in a flux vs. flux diagram in Fig. 3.

The nuclear reddening and host galaxy contamination to the total observed flux can be estimated using the flux variation gradient method [12] (see Fig. 3). This resulted in the determination of the

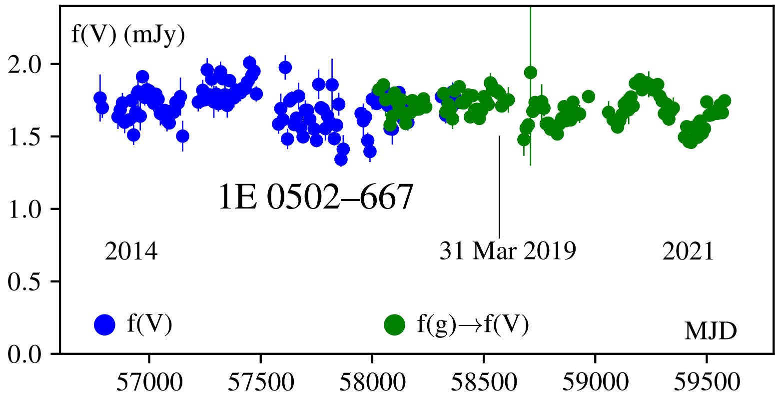

Figure 2: ASAS-SN light curve of 1E 0502–667 for the period 2014-2022. The g magnitudes have been adjusted to represent estimates of the corresponding V magnitudes.

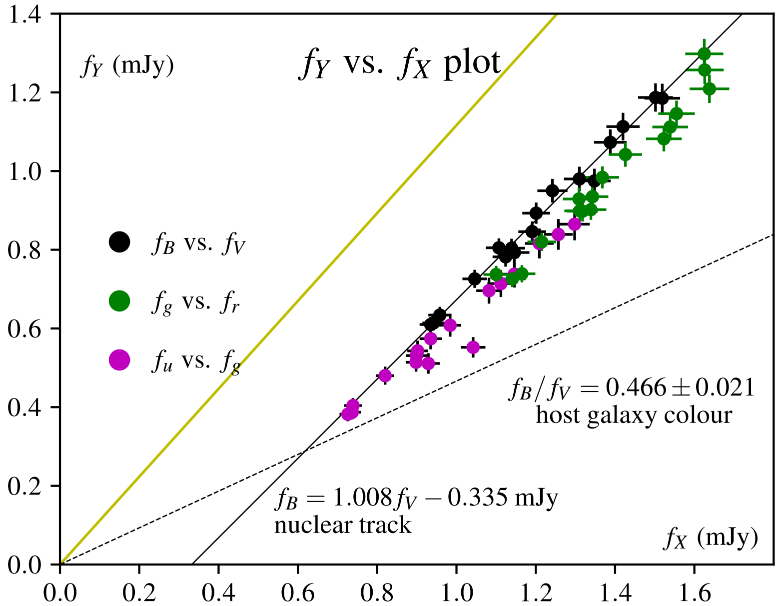

Figure 3: Flux variation gradient plots of LCOGT BVugr photometric measurements of 1E 0502–667. The solid line represents the best linear fit to the f_B vs. f_V plot, while the dashed line corresponds to the derived host galaxy colour (with uncertainty represented by the gold shading).

following nuclear colours: $B - V = 0.04 \pm 0.05$, $g - r = -0.09 \pm 0.06$, $u - g = 0.23 \pm 0.05$. The host galaxy colours may be estimated to be $(B - V)_g = 0.944$ from the photometry of the annulus with radii ranging from 2-3 arcsec. Employing the flux variation gradient method, this therefore yields a nuclear flux averaging ~ 0.6 mJy and varying with a standard deviation of ~ 0.2 mJy.

In addition to the optical flux measurements, it is also possible to examine the flux in other regions of the electromagnetic spectrum. Radio observations have been carried out at 843 MHz [13] and 2.3 GHz [14]. Infrared fluxed are available from WISE and 2MASS, while X-ray measurements from Chandra and ROSAT exist as well. The optical nuclear fluxes obtained by us link smoothly to the IR data with a profile consistent with the power law applied for the spectral analysis.

5. Discussion

The spectrum of 1E 0502–667 with its nearly total absence of narrow emission lines shows a striking similarity with that of the luminous nearby quasar 3C 273 [15], which is listed in the NASA/IPAC Extragalactic Database as having a magnitude of $V \sim 12.8$ and a redshift of $z = 0.158$. While not untypical for the most luminous quasars, having strong broad lines without the presence of narrow lines is extremely unusual in less luminous AGN. We have only been able to find one other AGN with redshift $z < 0.1$ that shares this property with 1E 0502–667, namely HE 1107–0813 [16].

The luminosity of 1E 0502–667 is however much lower that that of 3C 273. Comparing the V-magnitudes quoted earlier and combining these with the values of the redshifts means that 3C 273 is more luminous by a factor of ~ 150. As the ratio of 1E 0502–667's Hα-to-Hβ is close to the theoretical value of ~ 3 and the slope in Fig. 3 is ~ 1, its nucleus is essentially unreddened, meaning that the massive luminosity difference cannot be due to obscuration.

We conclude that 1E 0502–667 is indeed an unusual and remarkable AGN. The missing narrow lines in the spectra of distant quasars can be ascribed to the continuum and broad lines drowning out the narrow line component. In the case of 1E 0502–667, the apparent invisibility of the narrow lines point to intrinsically extremely weak emission from that component of the AGN. This may highlight a narrow line region that has not yet had time to develop fully, or that has otherwise been prevented from developing. In either scenario, this makes further study of 1E 0502–667 imperative.

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