













# Observations of the $\gamma$ -ray-emitting narrow-line Seyfert 1, SBS 0846+513, and its host galaxy

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## ABSTRACT

The  $\gamma$ -ray-emitting galaxy SBS 0846+513 has been classified as a narrow-line Seyfert 1 (NLS1) from its spectroscopy, and on that basis would be thought likely to have a small central black hole hosted in a spiral galaxy. However, very few of the  $\gamma$ -ray NLS1s have high-resolution imaging of their hosts, so it is unknown how the morphology expectation holds up for the  $\gamma$ -emitting class. We have observed this galaxy in the  $J$  band with the Large Binocular Telescope’s LUCI1 camera and the ARGOS adaptive optics system. We estimate its black hole mass to lie between  $4.2 \times 10^7 \leq \frac{M}{M_{\odot}} \leq 9.7 \times 10^7$ , using the correlation with bulge luminosity, or  $1.9 \times 10^7 \leq \frac{M}{M_{\odot}} \leq 2.4 \times 10^7$  using the correlation with Sérsic index. Our favoured estimate is  $4.2 \times 10^7 M_{\odot}$ , putting its mass at the high end of the NLS1 range in general but consistent with others that are  $\gamma$ -ray emitters. These estimates are independent of the broad-line region viewing geometry and avoid any underestimates due to looking down the jet axis. Its host shows evidence of a bulge + disc structure, from the isophote shape and residual structure in the nuclear-subtracted image. This supports the idea that  $\gamma$ -ray NLS1 may be spiral galaxies, like their non-jetted counterparts.

**Key words:** instrumentation: adaptive optics – galaxies: active – quasars: supermassive black holes – galaxies: Seyfert.

## 1 INTRODUCTION

The relation that links galaxies with the black hole (BH) at their centres has been known for a while, and it is valid for non-active and active galaxies (e.g. Ferrarese & Merritt 2000). The host galaxy of an active galactic nucleus (AGN) is the closest environment with which the nucleus interacts and co-evolves (Kormendy & Ho 2013). For example, accretion on to the central BH can ionize and heat the gas, suppressing the star formation (SF) in the circumnuclear region (Page et al. 2012). Simultaneously, the host directly affects the nuclear activity by regulating the gas supply of the BH. A remarkable example of this feedback is the interplay between the host and the relativistic plasma jet that can be launched by the BH. For example,

jets are observed digging their way through the host galaxy gas (Morganti et al. 2015), and they can efficiently suppress the SF activity far from the nucleus (Lanz et al. 2016). Although jets are crucial components in some AGNs, they are far from understood. Why and how they are formed are still unclear, but the host galaxy likely plays a role, directly or indirectly, in whether or not a jet is observed. In particular, powerful relativistic jets are preferentially, though not exclusively, associated with ellipticals (Laor 2000), and merging or interaction may be the keys that trigger the jet activity (Chiaberge et al. 2015).

An important new laboratory to study the jet phenomenon is the AGN class known as narrow-line Seyfert 1s (NLS1). Many of the sources referred to as NLS1s are actually *quasars* under the standard definition (total magnitude  $M < -23$ ), though this limit does not distinguish between the host and nuclear emission. The physical arguments regarding the NLS1 we expect to apply to

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narrow-line type-1 quasars, as well, and in this discussion, we refer to them collectively as NLS1. These objects were first classified by Osterbrock & Pogge (1985) and are defined by the low full width at half-maximum (FWHM) of H  $\beta$  ( $<2000 \text{ km s}^{-1}$ ; Goodrich 1989). The narrowness of permitted lines is believed to be due to the low rotational velocity around a low-mass black hole ( $<10^8 M_{\odot}$ ; Grupe & Mathur 2004). Other lines of reasoning support the idea of small BH masses for NLS1, including their X-ray power spectrum distribution (Pan et al. 2018) and the rapidity of their X-ray variability (Boller et al. 1997; Brandt et al. 1999; Yao et al. 2015; Gallo 2018). Taking into account their luminosity, comparable to that of broad-line Seyfert 1s (BLS1s), this is suggestive of a high Eddington ratio (Boroson & Green 1992). These properties have been interpreted as a sign of young age (Mathur 2000). If this is the case, NLS1s may be the low- $z$  analogue of the progenitors of high-mass AGN, sharing properties with early quasars.

However, it has been claimed that NLS1s are not genuinely young AGN (e.g. Sbarrato et al. 2018). Narrow permitted lines may also be due to the projection effects caused by a flattened broad-line region (BLR) observed pole-on (Decarli et al. 2008). Were this the case, the BH masses derived from spectral line widths (Calderone et al. 2013) would be underestimated. Fortunately, the host galaxy can help disentangling these two scenarios. Generally speaking, ellipticals tend to harbour more massive BH than spirals (e.g. Salucci et al. 2000), and the black hole mass correlates with properties of the bulge (e.g. Magorrian et al. 1998; Marconi & Hunt 2003; Graham & Driver 2007). So a measurement of the host galaxy type can tell us about the central black hole's mass in a way that is independent of geometry.

In 2009,  $\gamma$ -rays were detected from radio-loud NLS1 (Abdo et al. 2009), and in the years since, about 19 NLS1s have been detected with the *Fermi Gamma-Ray Space Telescope* (Romano et al. 2018; Järvelä et al. 2020). These have shown unambiguously that there exists a subset of NLS1s that are radio loud and have powerful, relativistic jets, even though with their smaller black holes, they may have been expected not to (Laor 2000). The  $\gamma$ -NLS1s are an intriguing and still poorly understood sample. If they are from the same broader population as the radio-quiet NLS1, then what triggers the relativistic jet? As described by Komossa (2018), a large number of  $\gamma$ -NLS1s seem to be in interacting systems. In fact, of the sources analysed in the study, only PKS 2004–447 and SBS 0846+513 did not show evidence for interaction at the then-available resolution. On the other hand, the majority of radio-quiet NLS1s do not show an excess of companion galaxies or evidence for mergers (Krongold, Dultzin-Hacyan & Marziani 2001; Xu et al. 2012). In general, jetted NLS1s preferably reside in denser regions than do the non-jetted NLS1 sources, at least in terms of large-scale environment (Järvelä, Lähtenmäki & Berton 2018).

Perhaps, the host galaxies are different between the radio-quiet NLS1 and the radio-loud NLS1 (especially the  $\gamma$  emitters). However, only a few studies have been dedicated to the hosts of NLS1s. Crenshaw, Kraemer & Gabel (2003) studied 19 NLS1s with *Hubble Space Telescope* (*HST*), all non-jetted at  $z < 0.084$ , finding a majority of spirals and frequent starburst rings. A high incidence of pseudo-bulges was found by Orban de Xivry et al. (2011) and confirmed by a subsequent study with *HST* of 10 more non-jetted sources up to  $z = 0.164$  (Mathur et al. 2012). However, nothing can be said for non-jetted sources at higher  $z$ . Regarding radio-loud, jetted NLS1s ( $\sim 7$  per cent of the whole NLS1 population; see Komossa et al. 2006), four sources have been studied individually (Zhou et al. 2007; Antón, Browne & Marchā 2008; Kotilainen et al. 2016; D'Ammando et al. 2017, 2018; Olguín-Iglesias et al. 2017; Berton et al. 2019).

A larger sample is that by Järvelä et al. (2018) with the Nordic Optical Telescope (NOT), but even in that case only three jetted sources were successfully resolved. In general, the results are still unclear. Most jetted NLS1s studied so far are hosted by spirals and disturbed morphologies. Doi et al. (2020) have analysed disturbed radio structures around 1H 0323+342 that support the idea that it lies in a post-merger host galaxy. The recent study by Olguín-Iglesias, Kotilainen & Chavushyan (2020) supports the merger idea generally. They image 29 radio-loud NLS1s, successfully detecting 21 and fitting bulge + disc models. However, a couple of NLS1s have been found to reside in non-interacting ellipticals (D'Ammando et al. 2017, 2018). This result may support the low-inclination scenario for NLS1s, and might contradict the relation between merging/interaction and jet formation, or it could be that visible signatures of past interaction have relaxed. It is clear that more examples are needed to shed light on the host–AGN connection.

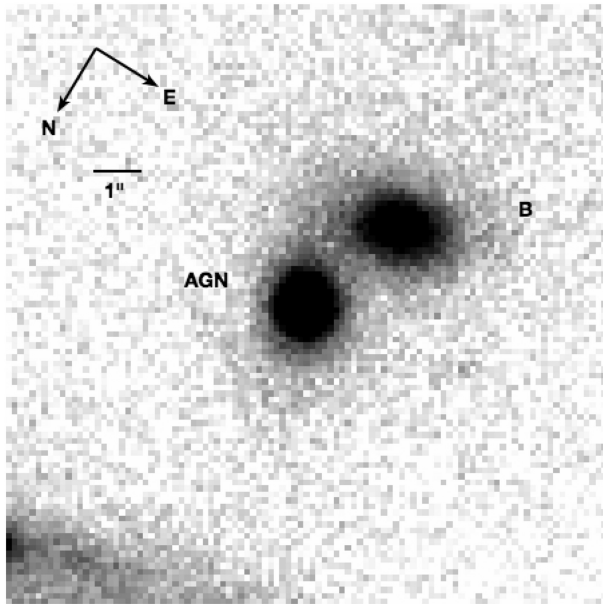
We selected SBS 0846+513 (RA =  $8^{\text{h}}49^{\text{m}}58^{\text{s}}.1$ , Dec. =  $+51^{\circ}08'25''.7$ ), a  $\gamma$ -ray-emitting NLS1<sup>1</sup> at  $z = 0.585$ , with the goals of observing the host galaxy's morphology and determining its black hole mass in a geometrically independent way. It was unresolved in existing imagery and did not show clear evidence of interaction, and the new observations would put it near the high-redshift end of  $\gamma$ -NLS1 imaged at high resolution. Its relatively high redshift makes any investigation with ground-based telescopes difficult, but adaptive optics is a great help. An important requirement for adaptive optics is the presence of a nearby bright reference star that can be used to model the wave front and correct the images for atmospheric distortion. However, most jetted NLS1s are located well outside the Galactic plane, and they do not have any suitable reference star in the vicinities. For this reason, we decide to observe SBS 0846+513 with the Advanced Rayleigh Guided Ground Layer Adaptive Optics System (ARGOS) on the LBT Utility Camera in the Infrared (LUCI1) camera mounted on the Large Binocular Telescope (LBT). This innovative system can produce a laser guide star that was used as reference for our observations.

The paper is organized as follows: The source is described in Section 2. In Section 3, we present the imaging and spectroscopic observations. The analysis is described in Section 4, including the galaxy modelling, isophote measurements, and black hole mass calculations. The discussion and interpretation are presented in Section 5.

## 2 SBS 0846+513

SBS 0846+513 was already identified as a potential blazar by Arp et al. (1979), although it was considered as a BL Lac at high redshift, and its correct distance was estimated only with the Sloan Digital Sky Survey (SDSS; Schneider et al. 2003). The source was already known for its extreme flaring activity, with a brightening of about 4 mag in approximately 1 month (Arp et al. 1979), which was initially attributed to gravitational lensing effects (Nottale 1986). The source was identified as an NLS1 by Zhou et al. (2006) and Yuan et al. (2008), given its H  $\beta$  FWHM of  $\sim 1800 \text{ km s}^{-1}$ , within the NLS1 definition. After the launch of *Fermi*, it was detected at  $\gamma$ -rays during its first observed flare (Donato & Perkins 2011; Foschini 2011). The black hole mass of SBS 0846+513 was estimated both using the FWHM and the second-order moment of H  $\beta$ , and in

<sup>1</sup>SBS 0846+513 has total absolute magnitude  $M < -23$ , so it is properly considered a quasar, but as we discussed above, we group Seyferts and quasars together in our discussions of NLS1.



**Figure 1.** *J*-band view of the field surrounding SBS 0846+513. SBS 0846+513 is marked ‘AGN’, and the projected companion ‘B’. At bottom, an arm from a large, foreground spiral can be seen. The scale bar spans 1 arcsec.

both cases the estimate is at  $\sim 3 \times 10^7 M_{\odot}$ , well within the typical range of NLS1s (Yuan et al. 2008; Foschini et al. 2015). At radio frequencies the source has been monitored for years, showing high amplitude variability both in flux and in polarization (Maune et al. 2014; Angelakis et al. 2015; Paliya et al. 2016). At kiloparsec scale, it presents a compact structure with no diffuse emission (Berton et al. 2018), while on parsec scale it shows a core-jet structure with superluminal motion and apparent velocity up to  $\sim 8c$  (e.g. Lister et al. 2016). Regarding its host galaxy, no significant structure was detected with the *HST* (Maoz et al. 1993) in an observation made before the telescope’s spherical aberration was corrected. Our new data are the first high-resolution observations of this source.

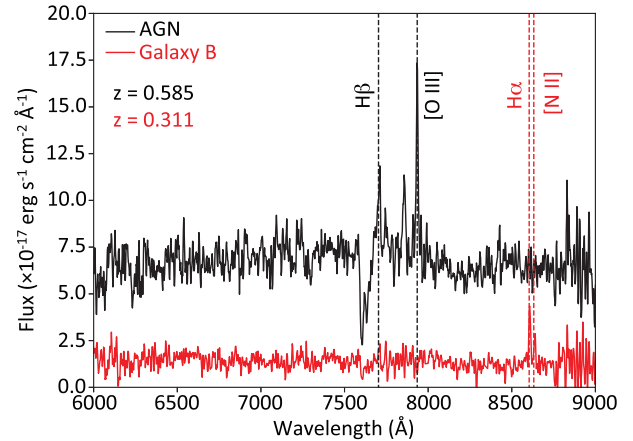
### 3 OBSERVATIONS

#### 3.1 Imaging

We observed SBS 0846+513 with the LUCI1 camera for two nights on 2016 December 14 and 15, as part of the commissioning run for ARGOS. LUCI1 and LUCI2 are twin instruments designed for both spectroscopy and imaging. In the imaging mode, they provide a  $4 \times 4$  arcmin field of view.

On December 14, we observed with the infrared *Ks* and *J* filters, but the seeing was bad and the images unusable. On December 15, we observed with the *J* filter only. On this night, the seeing and image quality were good, and we obtained a total exposure time of 31.7 min for the science observations, with individual exposures of 10 s each. The image scale is 0.118 arcsec per pixel. Building up a composite point spread function (PSF) from stars in the field, we obtain a PSF FWHM of 0.31 arcsec. The image reduction and PSF construction are described in Section 4.1.

The target region is shown in Fig. 1. The NLS1, SBS 0846+513, is marked ‘AGN’. Partially overlapping the AGN is a second galaxy, labelled ‘B’ in the image, that has a projected distance of 2.45 arcsec centre to centre.



**Figure 2.** NOT spectra of the AGN (upper line, black) and the apparent companion (lower line, red). Identified emission lines are marked with dashed, vertical lines:  $H\beta$  and  $[O\text{III}]$  in the AGN,  $H\alpha$ , and  $[N\text{II}]$  in the apparent companion. We measure a redshift of  $z = 0.585$  for the AGN and  $z = 0.311$  for galaxy B.

#### 3.2 Spectroscopy and redshift

Because galaxy B is projected to partially overlap the AGN, it raises the question of whether or not B is a physical companion, and possibly interacting. We addressed this spectroscopically, observing SBS 0846+513 with the Alhambra Faint Object Spectrograph and Camera (ALFOSC) on the NOT on 2018 May 9. The spectrum was obtained with a 1 arcsec slit oriented at a position angle of  $160^\circ$ , to fit both SBS 0846+513 and galaxy B in the slit at the same time. The spectrum interval covered was between 5650 and 10 150 Å, with a resolution ( $R$ ) of  $\sim 770$  and a total exposure time of 1800 s. After the standard bias and flat-field correction, the wavelength calibration was performed using a ThAr lamp. We flux calibrated the spectrum using as reference the standard star HD 93521.

The spectrum of the two sources is shown in Fig. 2. We clearly identify the AGN lines at  $z = 0.585$ , as expected. Both  $H\beta$  and  $[O\text{III}] \lambda\lambda 4959, 5007$  are clearly visible, next to the telluric absorption by the atmosphere. In the putative companion, instead, neither line is visible at the same wavelength. Instead, we detected at 8604 and 8631 Å, two narrow emission lines compatible with redshifted  $H\alpha$  and  $[N\text{II}] \lambda 6584$  at  $z = 0.311$ . In principle, the  $H\beta$  region and the  $[O\text{III}] 5007$  Å line would also be visible in galaxy B, but they are not detected in the spectrum, possibly suggesting the presence of internal absorption. Regardless of the reason these are not detected, galaxy B is definitely not at the same redshift as SBS 0846+513.

### 4 ANALYSIS

#### 4.1 Image processing

The data reduction process for producing the science image follows the steps described by Georgiev et al. (2019) in their ARGOS commissioning paper. After a basic reduction, correcting for non-linearity and persistence effects, bad pixel masking, and flat-fielding, sky frames were created from exposures spaced about 10 min apart in order to negate effects by the rapidly varying near-infrared atmosphere. The best 164 exposures were used in this case. Bright sources, such as stars and galaxies (with pixel values  $\sim 4\sigma$  above the background), were masked prior to combination. Several sky frames

**Table 1.** Statistics of sky and residuals. Columns: (1) Region or model residual. South, East, and West refer to source-free regions near the AGN. 1C (elliptical) and 2C (spiral) residuals have the total model subtracted from the image and use the fitting region centred on the AGN. (2) Mean value. (3) Minimum value. (4) Maximum value. (5) Standard deviation. (6) Distance of region from the AGN.

(1) Region	(2) Mean (ADU)	(3) Minimum (ADU)	(4) Maximum (ADU)	(5) $\sigma$ (ADU)	(6) Distance (arcsec)
East	1.47	-18.41	21.81	4.52	15
West	2.24	-20.32	16.1	4.41	16
South	3.03	-17.02	17.25	4.35	22
1C residual	0.00 <sup>a</sup>	-104.81	97.56	5.45	0
2C residual	0.01 <sup>b</sup>	-114.37	114.44	5.47	0

<sup>a</sup>Modelled sky level for the 1C model is 1.69 ADU.

<sup>b</sup>Modelled sky level for the 2C model is 1.82 ADU.

were used to subtract the sky in a group of exposures spaced within about 15 min.

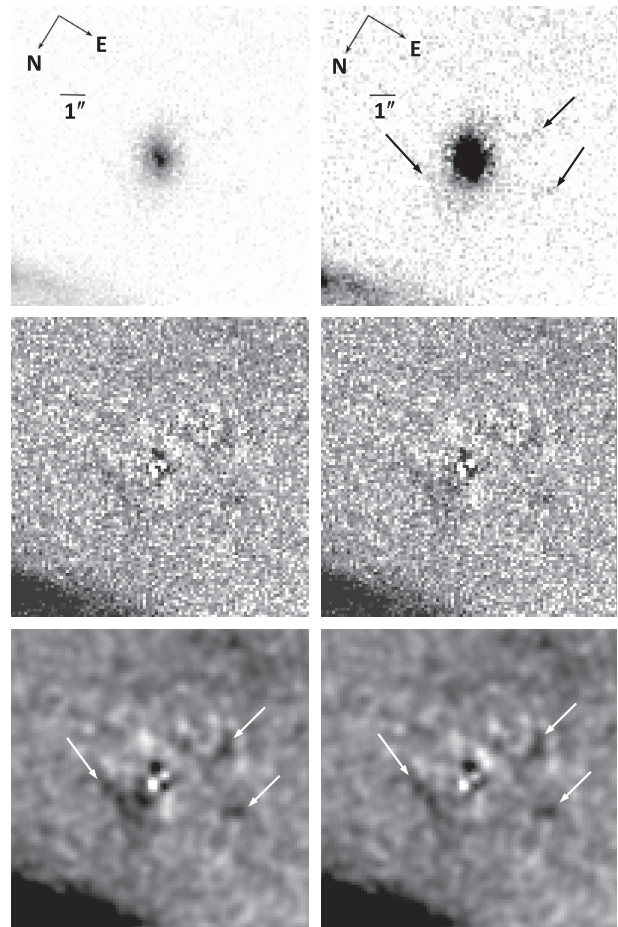
Due in part to the extended spiral galaxy nearby and its effect on the flat-fielding, the sky in source-free areas varies somewhat in the region around the AGN. At 15 arcsec east of the AGN, it has a mean of 1.47 analogue-to-digital units (ADU), 16 arcsec west of the AGN, the mean is 2.24 ADU, and 22 arcsec south of the AGN, the mean is 3.03 ADU. The large galaxy is to the north of the AGN, so no measurement is made there. The statistics for these regions are listed in Table 1. To minimize these effects in the analysis, we restrict the model fit (Section 4.3) to a region close to the AGN.

## 4.2 Photometric calibration

We calibrated the *J*-band magnitude system using the 2-Micron All Sky Survey (2MASS) Extended Source Catalog (XSC) and Point Source Catalog (PSC) (Skrutskie et al. 2006). Instrumental magnitudes for sources from our image were extracted with Source Extractor and compared to the 2MASS catalogues. Excluding the AGN (which is variable), galaxy B (which is merged with the AGN in 2MASS), and one bright star that is saturated, nine sources in this field are found in the PSC. Two of these are spiral galaxies and are also listed in the XSC. We adopt the XSC *J* magnitudes for these two and the PSC *J* magnitudes for the remaining seven. With these sources, we obtain a magnitude calibration with a standard deviation of  $\sigma = 0.26$  mag.

## 4.3 Host + nucleus modelling

Because this active galaxy has a bright nucleus, any study of its morphology requires a fit to both the nucleus – modelled with the PSF – and the host galaxy. We use GALFIT (Peng et al. 2011) to perform a two-dimensional fit to the image, simultaneously modelling the nucleus, the host galaxy, and galaxy B, with the sky fitted as a constant value. Because of the spatial variations in the sky described in Section 4.1, we perform the fit over a region spanning  $101 \times 101$  pixels ( $11.9 \times 11.9$  arcsec), centred on the AGN. This is wide enough to cover the visible extent of the AGN host and galaxy B but narrow enough so that the sky variation within the region is small. The large, foreground spiral seen in the north corner of Fig. 1 and the region of brighter sky to the south of galaxy B (which may include a low-surface-brightness source) are both masked out of the fit, as are smaller, dimmer clumps. The PSF model is constructed as a composite of 14 isolated stars from across the field of view and



**Figure 3.** Views of the AGN host galaxy and residuals, using an inverted colour scheme (blackier is brighter). The field of view is the same as in Fig. 1. Top row: The PSF and galaxy B models have been subtracted, showing the AGN host galaxy. Top left: Low-contrast image, showing the inner features of the host. Top right: High-contrast image, emphasizing the outer envelope. Three clumps of material are indicated by the arrows: a hook (south-east of the AGN), a round clump (east), and a line (tangent to the AGN, running from north-west to north). The round clump and line are just visible in Fig. 1 but are clearer here. The hook is hidden by galaxy B in the original image. Middle row: Elliptical (left) and spiral (right) residuals made by subtracting the total model. The brightness limits are set to  $\pm 3\sigma$  of the residual statistics. Bottom: Elliptical (left) and spiral (right) residuals with three-pixel Gaussian smoothing, with brightness limits at  $\pm 2\sigma$ . The three clumps of material (marked with arrows) are more visible.

has an FWHM of 2.6 pixels (0.31 arcsec). It spans  $53 \times 53$  pixels ( $6.2 \times 6.2$  arcsec) and is put into GALFIT with normal sampling.

To determine the morphology, two models of the host galaxy are tried. Model 1C is a one-component fit to the AGN host using a Sérsic model (elliptical galaxy), while model 2C performs a two-component fit to the host, using a Sérsic bulge and an exponential disc (spiral galaxy). The Sérsic index,  $n$ , is a free parameter in both cases. Galaxy B is best modelled with only single Sérsic component (with the index as a free parameter) in both cases, which leaves acceptably low residuals. The sky is modelled as a constant value; allowing it to ‘tilt’ across the field does not improve the fit. The host galaxy is shown in the PSF-subtracted residual image in Fig. 3, along with the total residuals, formed by subtracting the complete model from the image. The fitting results are summarized in Table 2 for the AGN and Table 3 for galaxy B, and the statistics of the residuals are

**Table 2.** Summary of AGN model fits. Columns: (1) Model type: 1C uses a one-component Sérsic fit to the AGN host, listed under ‘Bulge’. Model 2C uses two AGN host components – a Sérsic bulge and an exponential disc. (2) Reduced  $\chi^2$  of the fit. (3) Nuclear  $J$  magnitude. (4)–(11)  $J$  magnitude ( $m$ ), radius ( $r$ ), Sérsic index ( $n$ ), and ellipticity ( $\epsilon$ ) for host bulge and disc.  $1\sigma$  uncertainties are listed in brackets. Parameters that are held fixed are listed in parentheses. Subscripts  $p$ ,  $b$ , and  $d$  refer to nucleus (PSF), bulge, and disc, respectively.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Model	$\chi^2/\nu$	Nucleus (PSF)	Bulge				Disc			
		$m_p$ (mag)	$m_b$ (mag)	$r_b$ (arcsec)	$n_b$	$\epsilon_b$	$m_d$ (mag)	$r_d$ (arcsec)	$n_d$	$\epsilon_d$
1C (elliptical)	1.077	20.1 [ $<0.1$ ]	20.7 [ $<0.1$ ]	0.8 [ $<0.1$ ]	2.0	0.47	–	–	–	–
2C (spiral)	1.084	20.3 [ $<0.1$ ]	21.4 [ $<0.1$ ]	0.1 [ $<0.1$ ]	4.6	0.93	21.0 [ $<0.1$ ]	0.6 [ $<0.1$ ]	(1)	0.40

**Table 3.** Summary of model fits for galaxy B. Columns: (1) Model type (same as above). (2) Apparent  $J$  magnitude. (3) Half-light radius. (4) Sérsic index. (5) Ellipticity.  $1\sigma$  uncertainties are listed in brackets.

(1)	(2)	(3)	(4)	(5)
Model	$m_B$ (mag)	$r_B$ (arcsec)	$n_B$	$\epsilon_B$
1C	20.1 [ $<0.1$ ]	1.1 [ $<0.1$ ]	2.3	0.34
2C	20.1 [ $<0.1$ ]	1.1 [ $<0.1$ ]	2.3	0.34

listed in Table 1.

Absolute magnitudes and physical scales for both galaxies are presented in Table 4, using a cosmology of  $H_0 = 71$ ,  $\Omega_M = 0.27$ , and  $\Omega_{vac} = 0.73$ . At the AGN’s redshift, the scale is  $6.59 \text{ kpc arcsec}^{-1}$ , while for galaxy B, it is  $4.53 \text{ kpc arcsec}^{-1}$ . To calculate the absolute magnitudes, we adopt  $K$ -corrections for the AGN nucleus from Glikman, Helfand & White (2006) and for the AGN host and galaxy B from Mannucci et al. (2001). For the purposes of the  $K$ -correction, we assume that the AGN host is an E-type galaxy for the 1C model and an Sa-type galaxy for the 2C model, while galaxy B is treated as an Sa type.

In addition to the two-dimensional modelling, we examine the AGN’s radial profile and isophote structure. Figs 4 and 5 show the radial surface brightness ( $\mu$ ) profiles of the AGN for the 1C and 2C models, respectively, measured using IRAF’s `ellipse` task with circular annuli. Plots are included of the image (with the sky and the galaxy B model subtracted), the total model, and the separate components of that model – the host model (1C: Sérsic only; 2C: Sérsic bulge and exponential disc) and the nuclear model (stellar PSF). The profile is taken out to an angular distance of 2.1 arcsec from the centre of the nucleus, corresponding to a projected distance of 14 kpc at the redshift of the source. The bottom portion of the figure shows the difference between the image and the total model for each isophote:  $\Delta\mu = \mu_{\text{image}} - \mu_{\text{total model}}$ .

IRAF’s `ellipse` task is also used to measure the Fourier  $a_4/a$  parameter of the host galaxy isophotes. The galaxy B and scaled PSF models produced by GALFIT are subtracted from the image, and elliptical isophotes are fitted to the host that remains. Negative values of  $a_4/a$  indicate boxiness in a given isophote, a more rectangular deviation from an ellipse, while positive values indicate discy, lemon-shaped isophotes. An overall discy trend to the isophotes is associated with the presence of galactic discs. The radial  $a_4/a$  plots are presented in Figs 6 and 7, using the elliptical model and spiral model assumptions, respectively. The convolution of the bright centre of the galaxy with the PSF biases the shape of the innermost isophotes, so we do not plot isophotes closer than 0.3 arcsec (2 kpc) from the centre. The vertical axis is scaled by a factor of  $100\times$ , and the dashed horizontal line at  $a_4/a = 0$  separates the positive (discy) values from negative (boxy) values.

#### 4.4 Black hole mass

We use three methods to determine the central black hole mass – the correlation with the host bulge, and two correlations with the Sérsic index. Detailed results are shown in Table 5. The relationship between host spheroidal luminosity and black hole mass is given by Marconi & Hunt (2003) as

$$\log \frac{M_{\text{BH}}}{M_{\odot}} = a + bX, \quad (1)$$

where for the  $J$  band,  $a = 8.26 \pm 0.07$ ,  $b = 1.14 \pm 0.12$ ,  $X = \log L_{J,\text{bulge}} - 10.7$ ,  $M_{\text{BH}}$  represents the black hole mass,  $M_{\odot}$  is the Sun’s mass, and  $L_{J,\text{bulge}}$  is the  $J$ -band spheroidal luminosity. In terms of spheroidal magnitude,  $M_{J,\text{bulge}}$ , this becomes

$$\log \frac{M_{\text{BH}}}{M_{\odot}} = 0.46(M_{J,\odot} - M_{J,\text{bulge}}) - 3.94. \quad (2)$$

Using  $M_{J,\odot} = 3.67$  for the Sun’s magnitude, we obtain a black hole mass of  $9.70 \times 10^7 M_{\odot}$  for the 1C model and  $4.17 \times 10^7 M_{\odot}$  for the 2C model.

The radial profile method of Graham & Driver (2007) correlates the Sérsic index,  $n$ , with the black hole mass. They fit both linear (their equation 4) and quadratic (their equation 7) relationships to the data. The linear fit gives

$$\log \frac{M_{\text{BH}}}{M_{\odot}} = (2.68 \pm 0.40) \log \frac{n}{3} + (7.82 \pm 0.07), \quad (3)$$

while the quadratic fit is

$$\log \frac{M_{\text{BH}}}{M_{\odot}} = (7.98 \pm 0.09) + (3.70 \pm 0.46) \log \frac{n}{3} - (3.10 \pm 0.84) \left( \log \frac{n}{3} \right)^2. \quad (4)$$

As shown in Table 5, model 1C leads to a mass of  $2.37 \times 10^7 M_{\odot}$  for the linear fit or  $1.90 \times 10^7 M_{\odot}$  for the quadratic fit. Since the two-component model bulge is smaller than the PSF width, we do not calculate profile-derived masses for model 2C.

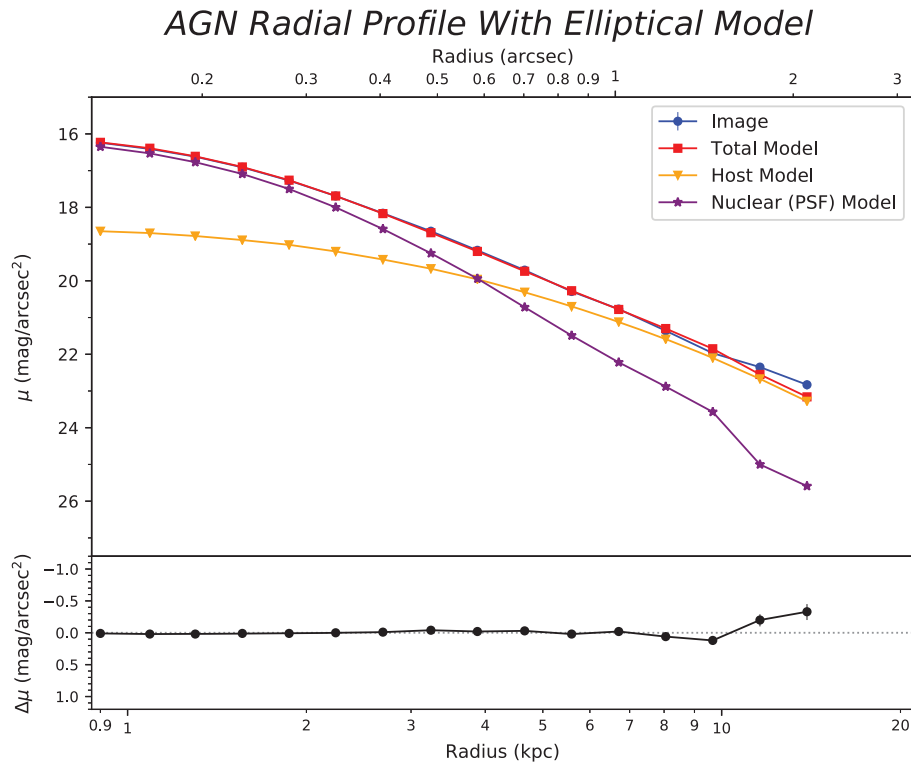
## 5 DISCUSSION

### 5.1 Host galaxy

In interpreting the relationship of these  $\gamma$ -ray emitters to the broader population of NLS1, it is important to compare their morphologies. However, very few of the  $\gamma$ -ray emitters’ hosts have been resolved, because the fraction of NLS1 known to emit  $\gamma$ -rays peaks at  $z \sim 0.5$ – $0.7$ , where their hosts become harder to distinguish, and high-resolution observations such as these are necessary. NLS1s at low redshift have been found to reside primarily in spiral galaxies, similar to the overall population of Seyfert 1s. Crenshaw et al. (2003) and

**Table 4.** Derived quantities for the AGN and galaxy B. Columns: (1) Model (same as above). (2)  $J$ -band absolute magnitude of the AGN nucleus. (3)–(6)  $J$ -band absolute magnitudes ( $M$ ), and radii ( $r$ ), for the AGN bulge and disc. (7)–(8) Bulge-to-total ratio and total absolute magnitude for the AGN host. (9)–(10)  $J$ -band absolute magnitude and radius for galaxy B.  $1\sigma$  uncertainties are listed in brackets. Subscripts are the same as above.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Model	Nucleus $M_n$ (mag)	Bulge $M_b$ (mag)	Bulge $r_b$ (kpc)	Disc $M_d$ (mag)	Disc $r_d$ (kpc)	$B/T$	$M_{\text{host}}$ (mag)	Galaxy B $M_B$ (mag)	Galaxy B $r_B$ (kpc)
1C	−22.6	−22.3	5.6 [0.2]	–	–	1.00	−22.3	−21.1	4.8 [0.1]
2C	−22.4	−21.5	0.6 [0.1]	−21.9	3.8 [0.1]	0.41	−22.4	−21.1	4.8 [0.2]



**Figure 4.** Radial surface brightness ( $\mu$ ) plot of the AGN image and components for the 1C (Sérsic) model, using circular annuli. The upper plot shows the profiles of the image (with the sky and the galaxy B model removed), the total model, and the model’s individual components. The lower plot shows the difference in surface brightness between the image and the total model ( $\Delta\mu = \mu_{\text{image}} - \mu_{\text{total model}}$ ). The horizontal axis is marked in both arcseconds (top scale) and projected kpc for the redshift of the AGN (bottom scale) for both plots. The vertical range is scaled to match Fig. 5 for ease of comparison. Error bars are given for the image and  $\Delta\mu$ . The single Sérsic model provides a good match to the profile over most of the range but underestimates the light in the image beyond about 1.5 arcsec (10 kpc).

Deo, Crenshaw & Kraemer (2006) have only one clear E type in their NLS1 samples. Olgún-Iglesias et al. (2017) has one classified as SB0.

How does SBS 0846+513’s morphology compare to lower redshift NLS1, which are primarily found in spiral galaxies? As shown in Table 2, the one-component (1C, elliptical) and two-component (2C, spiral) models of the AGN have similar goodness of fit. The elliptical model finds the AGN host galaxy to have an overall Sérsic index of  $n = 2.0$ , making it flatter than a de Vaucouleurs profile ( $n = 4$ ). The spiral model uses an exponential disc and finds the bulge to have a higher Sérsic index of 4.6, but the bulge is smaller than the PSF width, so we cannot do much interpretation of it. The bulge-to-total ratio of 0.41 (found in Table 4) is consistent with an Sa or Sab Hubble type (Weinzirl et al. 2009). While the elliptical model has a slightly lower goodness of fit than the spiral, they are so close that a preference based on  $\chi^2/\nu$  would

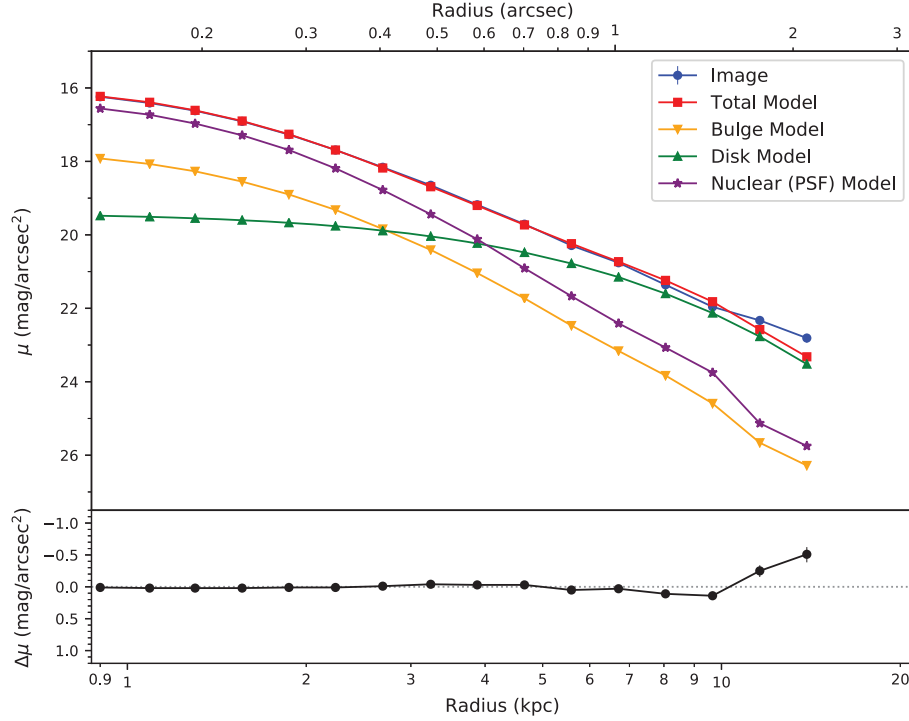
be an overinterpretation, and we use other criteria, as discussed below.

Using the 6dF luminosity function of Jones et al. (2006) and a Hubble constant of  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , we obtain  $M_j^* = -23.6$ , while the host galaxy of SBS 0846+513 has a total magnitude of  $-22.3$  (elliptical model) or  $-22.4$  (spiral).<sup>2</sup> This puts the host at 1.2–1.3 mag fainter than  $M_j^*$ .

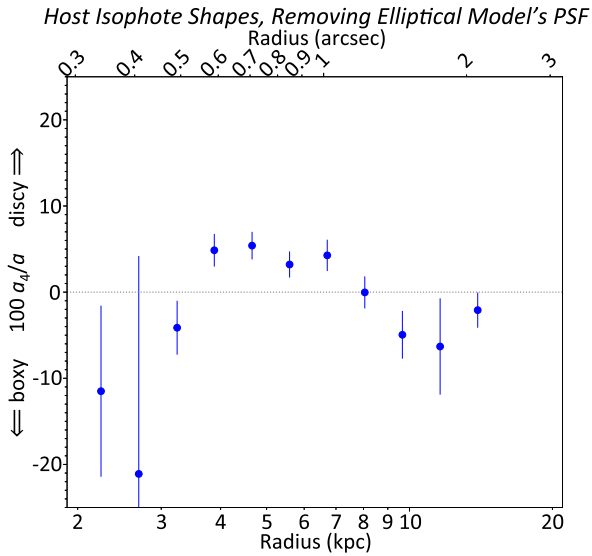
The radial profiles in Figs 4 and 5 show a good fit to the image by the elliptical and spiral models, respectively, out to about 1.5 arcsec (10 kpc). Beyond this radius, there is extra light in the image that is unaccounted for by either model. This appears to come from a linear

<sup>2</sup>The small discrepancy comes from the different  $K$ -corrections for the morphologies.

### AGN Radial Profile With Spiral Model



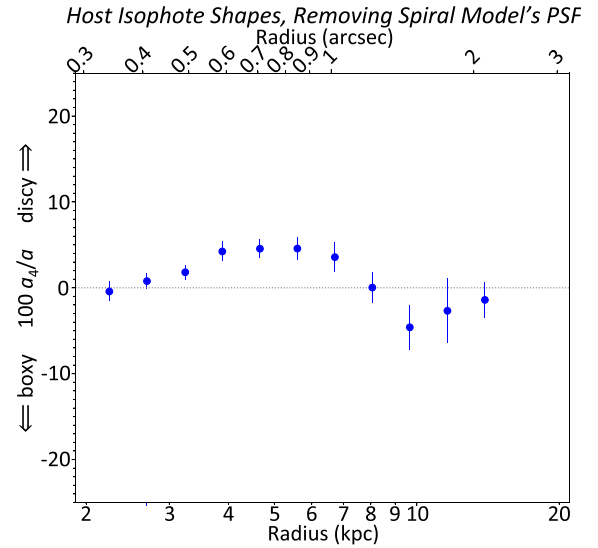
**Figure 5.** Radial surface brightness ( $\mu$ ) plot of the AGN image and components for the 2C (Sérsic bulge + exponential disc) model. The plot layout and scale are the same as in Fig. 4. Like the elliptical galaxy model, this spiral model also provides a good match to the profile over most of the range but underestimates the light in the image beyond about 1.5 arcsec (10 kpc).



**Figure 6.** Isophote boxiness/disciness parameter for the AGN host, as a function of semimajor axis. Negative values of  $a_4$  indicate boxiness, while positive values indicate disciness. Galaxy B and the PSF have been removed, using the scaling in the elliptical model. The shapes of the inner isophotes ( $r \lesssim 0.5$  arcsec) are likely affected by the specifics of the PSF subtraction. Outside this radius, the parameter rises to a peak at  $a_4/a = 0.054$ , which corresponds to a discy shape.

clump of material, visible in the residual images shown in Fig. 3. These clumps will be discussed in more detail below.

We next examine the radial variation of the isophotes'  $a_4/a$  parameter (Figs 6 and 7), which is associated with boxy (negative)



**Figure 7.** Same as Fig. 6, but subtracting the galaxy B and PSF components from the spiral model. The axis ranges are kept the same to aid in comparison. The fainter PSF in the spiral model leads to the smaller parameter values in the inner isophotes ( $r \lesssim 0.5$  arcsec), while the outer values are similar to those in the elliptical case. The peak value is  $a_4/a = 0.046$ , again corresponding to a discy shape.

or discy (positive) isophotes. The galaxy B and PSF models are subtracted from the image before the elliptical isophotes are fitted to the host, and the only significant difference comes from the PSF scaling. The PSF is slightly fainter in the spiral model, leading to the difference in the inner isophote parameters ( $r \lesssim 0.5$  arcsec) in

**Table 5.** Central black hole mass of the AGN, calculated by different methods: ‘Bulge luminosity’ is the black hole mass/bulge luminosity relation; ‘Sérsic linear’ is the linear fit to the black hole mass/Sérsic index relation; ‘Sérsic quadratic’ is the quadratic fit to the latter. Models are the same as above. Mass uncertainties (listed in brackets) account for uncertainties in the proxy and statistical uncertainties in the input parameter, but they cannot account for systematic errors in the input parameter.

Method	Model	$\log(M_{\text{BH}}/M_{\odot})$
Bulge luminosity	1C	7.99 [0.08]
Bulge luminosity	2C	7.62 [0.11]
Sérsic linear	1C	7.37 [0.11]
Sérsic quadratic	1C	7.28 [0.13]

the two cases. Outside this radius, we see that  $a_4/a$  rises to a broad, positive peak between 0.6 and 1.0 arcsec in both scenarios, going negative in the outermost radii. The peak value is  $a_4/a = 0.054$  in the elliptical scenario and 0.046 in the spiral scenario, so by using the criteria of Bender et al. (1989), we can assign a characteristic value of  $a_4/a \sim 0.05$ , and this strengthens the evidence for a galactic disc.

In Fig. 3, we show residuals created by subtracting the PSF and galaxy B models (top row) and the total model (middle and bottom rows) from the image. In the top row, we can see some clumps of material, marked by arrows, and these are clearer in the total residual images. A hook-shaped feature is to the south-east of the AGN, a round clump is to the east, and a linear feature runs from north-west to north, tangent to the AGN host. The linear feature appears to be responsible for the extra light in the image starting at 1.5 arcsec. This could be a companion galaxy or it might be that both the linear and hook features are part of a spiral pattern in the host. They are on opposite sides of the AGN at about the same distance from the nucleus, but their shapes are not symmetrical and could show a disturbance. The fact that the linear feature (and perhaps both of them) causes a divergence from the model profile could mean that these are tidal or otherwise caused by an interaction. The round clump is masked from the AGN fits, but we do not attempt to model any of these clumps separately, because they are only of low significance ( $\leq 1\sigma$  above sky level). It would be interesting to see them in a deeper image.

Another interpretation of the hook pattern could be as a feature of galaxy B. The outer isophotes of this galaxy have a slightly asymmetrical appearance to the eye, extending a bit farther to the west than the east. Our attempts to account for this in GALFIT (such as adding Fourier components or a non-concentric bulge and disc) either fail to improve the fit or kept it from converging.

The residual statistics for the unmasked regions are listed in the bottom two rows of Table 1. There is no systematic offset from the sky level, though there is a higher standard deviation compared to the neighbouring source-free regions. Some of this comes from noise in the PSF model for the nucleus, which is scaled in brightness during the fit. Both models leave residuals with essentially identical standard deviations. The brighter region to the south of galaxy B, an area masked from the model fit, includes some low-surface-brightness sources that are just outside the cropped field.

So in its morphology, SBS 0846+513 does not appear obviously different from the common spiral galaxies of low-redshift NLS1, though there is some ambiguity. The elliptical (1C) and spiral (2C) models have very similar goodness of fit. However, the isophotes show a discy structure in their Fourier components, and there are possible indications of spiral structure. Thus, we tentatively conclude that the host of SBS 0846+513 is a spiral galaxy. The bulge in the spiral model is too compact to be fully resolved, so we cannot tell if it is a pseudo-bulge, as is found in so many low-redshift NLS1s.

Either deeper ground-based observations with full adaptive optics or space-based observations with the *HST* or the *James Webb Space Telescope* would improve the resolution and the model, allowing a better comparison.

## 5.2 AGN environment

We considered whether or not SBS 0846+513 has a companion, perhaps involved in a merger that could have triggered its active phase. In Fig. 1, we see that galaxy B is separated from SBS 0846+513 by a projected distance of 2.45 arcsec. Their proximity has caused problems in the past. In fact, SBS 0846+513 was once (Hewitt & Burbidge 1989) placed at a redshift of  $z = 1.86$ , due to the contamination of its spectrum by galaxy B, whose redshift was roughly modelled as 0.235 in prior papers. At the resolution of the LBT, there is still a very slight overlap, and the possibility of a merger is interesting, given the role mergers sometimes play in triggering AGN.

From our spectroscopy (Section 3.2), we find that the redshift of SBS 0846+513 is  $z = 0.585$ , using H  $\beta$  and [O III] lines, but the redshift of galaxy B is 0.311, using H  $\alpha$  and [N II] lines. So the two galaxies are only visual companions, which are not interacting with each other.

Some of the three features marked in Fig. 3 could be dwarf companions of the AGN. If so, it would be consistent with the studies that show that a majority of  $\gamma$ -NLS1s have signs of mergers or interactions (Komossa 2018). The round clump to the east lies at a projected distance of 23 kpc (3.5 arcsec) from the AGN. We have leaned towards interpreting the linear and hook features as arms of the AGN host, but it is possible they are also companions, if they are at the AGN redshift at all.

## 5.3 Black hole mass

Earlier mass estimates for SBS 0846+513 have come from a variety of methods. Zhou et al. (2005) puts its mass at  $8.2 \times 10^6 M_{\odot}$  using the BLR H  $\beta$  linewidth,  $5.2 \times 10^7 M_{\odot}$  using the  $M_{\text{BH}}-\sigma_*$  relation with the narrow-line region [O III] to get stellar motion in the bulge, or  $4.3 \times 10^7 M_{\odot}$  using the  $M_{\text{BH}}-M_{\text{bulge}}$  relation with the elliptical galaxy mass-to-light ratio and a host template spectrum. Yuan et al. (2008) obtain  $2.5 \times 10^7 M_{\odot}$  using the BLR H  $\beta$  linewidth, which is close to the  $3.2 \times 10^7 M_{\odot}$  calculated by Foschini et al. (2015). Using the estimates of black hole mass uncertainties by Vestergaard (2004), both of these are consistent with the non-BLR masses of Zhou et al. (2005). Shen et al. (2011) derive mass estimates for SBS 0846+513 based on SDSS spectra, including H  $\beta$  and Mg II-derived masses by a variety of calibrations. These range from  $5.6-9.7 \times 10^7 M_{\odot}$ . These are slightly higher than the masses discussed above, but given their uncertainties, the low end of this range is consistent with the H  $\beta$  estimate of Zhou et al. (2005).

As mentioned in Section 1, it has been argued that the narrow widths of NLS1s’ permitted lines might not be due to smaller black hole masses but to geometry – that these galaxies are viewed nearly pole-on to a disc-like BLR, minimizing the Doppler effects and leading to an underestimate of the black hole mass. In  $\gamma$ -ray-emitting NLS1s, at least, we are more likely to have a nearly pole-on view of the black hole, since we must be looking along the radio jet. However, since we are able to resolve much of the host galaxy in the case of SBS 0846+513, we can derive measures of the black hole mass that are independent of the BLR flattening and orientation, using the correlations with bulge luminosity and radial profile. We should note that the arguments that NLS1 black hole masses are underestimated have been countered in more recent



literature [Foschini (2020) provides a thorough review, and see our discussion below], so there is much less controversy today. However, we believe it is useful to put a geometry-independent mass estimate in this context.

Our masses derived from all methods are listed in Table 5. The mass–luminosity relation of the bulge gives us our highest estimates,  $9.7 \times 10^7 M_{\odot}$  for the elliptical (1C) model and  $4.2 \times 10^7 M_{\odot}$  for the spiral (2C) model, and these lie within the range of estimates from prior work on this AGN. For spiral galaxies, the mass–luminosity relation assumes a classical bulge, and pseudo-bulges tend to have smaller black hole masses for their luminosity (Mathur et al. 2012). Since the bulge in our spiral model is effectively unresolved (the effective radius is narrower than the PSF), we do not know if it is classical or pseudo, and so the black hole mass could be lower.

The Sérsic index method applied to the elliptical host model gives results that are very similar to each other, whether we use the linear or the quadratic version:  $1.9\text{--}2.4 \times 10^7 M_{\odot}$ , lower than those of the bulge luminosity method. We only apply this method to the elliptical model, because the bulge in the spiral model is not fully resolved, and a structural parameter is unreliable.

So the biggest variation in the mass estimates comes from choosing either the bulge luminosity method or the Sérsic index method. Because we believe the host galaxy is a spiral, we prefer the mass derived for the 2C model using the bulge luminosity method,  $4.2 \times 10^7 M_{\odot}$ . In the end, all of our estimates are consistent with previous results. This indicates that the H  $\beta$ -derived masses for this source are *not* underestimated.

How does the mass of SBS 0846+513 compare with other NLS1s in general and  $\gamma$ -ray emitters in particular? Its  $\gamma$ -ray emission likely comes from a powerful relativistic jet, and jet power scales with black hole mass (see e.g. Heinz & Sunyaev 2003), so we might expect it to be more massive than the typical non-jetted NLS1. Based on a sample selected by Rakshit et al. (2017), Berton et al. (2020) report on their study of 3933 NLS1s whose H  $\beta$  lines fit a Gaussian or Lorentzian profile, using the SDSS data extending out to a redshift of  $z = 0.8$ . Of these, none has a black hole mass greater than  $10^8 M_{\odot}$ . Our favoured mass estimate for SBS 0846+513 (using the bulge luminosity method with the spiral model) would make it more massive than all but 3.4 per cent (132 out of 3932) of the complete Berton et al. (2020) sample. A better comparison would account for the variation in mass distribution with redshift. Restricting ourselves to sources within a redshift range of  $\pm 0.1$  from SBS 0846+513 ( $0.485 < z < 0.685$ ), we see that it is more massive than all but 9.0 per cent (70 out of 776) of NLS1s in that range. Regarding  $\gamma$ -ray-emitting NLS1, there are four in the list of Romano et al. (2018) that are within  $z \pm 0.1$  of our target and which have published black hole masses (see Berton et al. 2016; Paliya et al. 2018). These masses range from  $2.3\text{--}6.6 \times 10^7 M_{\odot}$ , putting our source’s preferred mass in the middle of the range.

Komossa (2018) compiles mass estimates for two  $\gamma$ -NLS1s (1H 0323+342 and PKS 1502+036) whose black holes have been measured with several techniques, including host galaxy correlations (original host analyses by León Tavares et al. 2014 and D’Ammando et al. 2018, respectively), single-epoch H  $\beta$  spectroscopy, SED modelling, and others. It is interesting to note that the host-galaxy-derived methods return much higher masses than the single-epoch H  $\beta$  spectra in those cases: by one order of magnitude for 1H 0323+342 and by two orders of magnitude for PKS 1502+036. In fact, the host galaxy correlations lead to the highest mass estimates of *any* of the methods on the list. Since single-epoch spectra are orientation dependent while the host galaxy methods are not, one possibility is that the spectra are underestimating the black hole mass. However, the H  $\beta$  results in these two cases are more consistent with mass

results from several other methods, as we expect. The consistency is good for 1H 0323+342; in the case of PKS 1502+036, the H  $\beta$  result returns the lowest mass of four methods across seven studies, but the greatest difference is between H  $\beta$  and the host galaxy result.

On the other hand, the host galaxy methods could be overestimating the black hole mass. León Tavares et al. (2014) find similar goodness of fit for the elliptical (bulge) and spiral (bulge + disc) models for 1H 0323+342’s host, and they choose the elliptical model for simplicity. The bulge in the *J*-band spiral model is 1.5 mag fainter than that in the elliptical model, and it has a Sérsic index of  $n = 0.88$ , which is consistent with a pseudo-bulge. For PKS 1502+036, D’Ammando et al. (2018) find a lower  $\chi^2/\nu$  for their spiral model than the elliptical model. Choosing the spiral would make the bulge 0.4 mag fainter. The Sérsic index is fixed at  $n \equiv 4$  in this case, so we cannot tell from their report if the bulge would be classical or a pseudo-bulge. However, Olguín-Iglesias et al. (2020) find a spiral host with a bulge whose Sérsic index is close to 1, indicating a pseudo-bulge and decreasing the black hole mass. In both of these cases, then, using the spiral model to derive the black hole mass would be justifiable, and it would return a lower result.

It would be interesting to make more general comparisons between the masses of the known  $\gamma$ -NLS1 and the non- $\gamma$  emitters, but we must be cautious using even the H  $\beta$ -derived masses for each group, because of different assumed values for the virial factor,  $f$ . For example, the Berton et al. (2020) sample of NLS1 uses  $f = 3/4$ , while the  $\gamma$ -NLS1 masses of Foschini et al. (2015) are calculated using  $f = 3.85$ . Since  $f$  is related, in part, to the inclination angle of the BLR, and the  $\gamma$ -NLS1 must be viewed close to pole-on, then these different values may be appropriate. However, more work is needed, and it would be good to have a larger set of orientation-independent measures of black hole mass as a comparison.

It should be noted that there is a very strong statistical argument that the majority of NLS1 cannot have BH masses as high as BLS1 and simply be underestimated due to their geometry. As pointed out by Komossa et al. (2006), if NLS1s were just the face-on analogues of BLS1s and narrower Balmer line widths because the BLR was flattened and viewed close to pole-on, then we should see a large fraction of beamed NLS1s. In fact, more NLS1s would be seen as beamed than BLS1s, because they would be the population with more face-on sources. Yet the opposite is the case. Studies consistently find that the fraction of radio-loud sources is smaller in NLS1s.

So SBS 0846+513 has a massive black hole of about  $4.2 \times 10^7 M_{\odot}$ , larger than most NLS1s, but consistent with estimates of the other  $\gamma$ -ray-emitting NLS1s in its redshift range. All of our mass estimates for this source are consistent with the range of H  $\beta$ -derived values, indicating that the single-epoch spectra are not leading to an underestimate of its mass.

#### 5.4 Variability

SBS 0846+513 shows strong variability at all wavelengths, from radio (e.g. Angelakis et al. 2015) to mid-IR (see Caccianiga et al. 2015) to  $\gamma$ -rays (see Foschini et al. 2015). Comparing the photometry of SBS 0846+513 between our observations and the 2MASS XSC, we see that the AGN nucleus has dimmed significantly since the 2MASS observation of 1998 December 23. The 2MASS observations are not able to resolve the AGN and galaxy B, so we subtract the light we measure for the host galaxies of these two and find the nucleus in 1998 had  $J = 15.9$ , regardless of the host model we assume. So it has dimmed by 4.4 (4.2) mag to  $J = 20.3$  (20.1) we observed on 2016 December 15, using the spiral (elliptical) model. SBS 0846+513 is known to have exceptional changes in the optical (e.g. the 4-mag

variation in about a month recorded by Arp et al. 1979), so this level of variability is not unusual for this object and is well within the historical range.

## 6 CONCLUSIONS

We observed the NLS1 galaxy SBS 0846+513 in the  $J$  band with the LUCI camera, aided by laser-guide ground-layer adaptive optics system, ARGOS, on the LBT. The galaxy has a significant  $\gamma$ -ray emission, likely from a relativistic jet. Very little is known about the host galaxies of the  $\gamma$ -NLS1 and how they fit into the broader population of normal NLS1.

The host galaxy is resolved, and the elliptical and spiral host models have similar goodness of fit. We see evidence for what may be spiral arms, and the host has discy isophotes, which argue for a bulge + disc host galaxy. This is consistent with most NLS1s at lower redshift, even though relativistic jets are more common in ellipticals. Space-based observations from the *HST* or the *James Webb Space Telescope* would be useful to improve the resolution of the host, model the bulge, and look for signs of galaxy interactions.

Using correlations between black hole mass on the one hand and bulge luminosity and Sérsic index on the other, we find it harbours a central black hole with a mass likely around  $4.2 \times 10^7 M_{\odot}$ . This measurement is independent of the viewing angle to the BLR and therefore avoids any biases due to BLR geometry, and it indicates that the  $H\beta$ -derived masses for this object are not underestimated. The mass lies at the high end of the normal NLS1 range but is consistent with other  $\gamma$ -NLS1 masses.

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## DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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