The disc–like host galaxies of radio loud Narrow-Line Seyfert 1s

Alejandro Olguín–Iglesias,1,⋆ Jari Kotilainen,2,3 Vahram Chavushyan1
1 Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis E. Erro 1, Tonantzintla, Puebla, México, C.P. 72840
2 Finnish Centre for Astronomy with ESO (FINCA), Vesilinnantie 5, FI-20014 University of Turku, Finland
3 Department of Physics and Astronomy, Vesilinnantie 5, FI-20014 University of Turku, Finland

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
Until recently, relativistic jets were ubiquitously found to be launched from giant elliptical galaxies. However, the detection by the Fermi–LAT of γ−ray emission from radio–loud narrow–line Seyfert 1 (RL–NLSy1) galaxies raised doubts on this relation. Here, we morphologically characterize a sample of 29 RL–NLSy1s (including 12 γ−emitters, γ−NLSy1s) in order to find clues on the conditions needed by AGN to produce relativistic jets. We use deep near-infrared images from the Nordic Optical Telescope and the ESO VLT to analyze the surface brightness distribution of the galaxies in the sample. We detected 72% of the hosts (24% classified as γ−NLSy1s). Although we cannot rule out that some RL–NLSy1s are hosted by dispersion supported systems, our findings strongly indicate that RL–NLSy1s hosts are preferentially disc galaxies. 52% of the resolved hosts (77% non γ−emitters and 20% γ−emitters) show bars with morphological properties (long and weak) consistent with models that promote gas inflows, which might trigger nuclear activity. The extremely red bulges of the γ−NLSy1s, and features that suggest minor mergers in 75% of their hosts, might hint to the necessary conditions for γ−rays to be produced. Among the features that suggest mergers in our sample, we find 6 galaxies that show offset stellar bulges with respect to their AGN. When we plot the nuclear versus the bulge magnitude, RL–NLSy1s locate in the low–luminosity end of flat spectrum radio quasars (FSRQs), suggesting a similar accretion mode between these two AGN types.

Key words: galaxies: active – galaxies: bulges – galaxies: Seyfert – galaxies: structure – gamma-rays: galaxies

1 INTRODUCTION
Because of the tight empirical relations observed between the black hole mass and different properties of its host galaxy bulge (Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002; Gültekin et al. 2009), it is now widely accepted that there is a strong connection between the supermassive black holes (SMBHs) and their host galaxies. The link between the black hole and its host galaxy is thought to be the AGN activity, through feedback processes (either positive or negative; for a review see Fabian 2012; Heckman & Best 2014). If this is the case, then, we can assume that the more powerful the AGN, the stronger the influence on its host galaxy. In fact, a study by Olguín-Iglesias et al. 2016 (performed on 0.3 < z < 1.0, strongly beamed AGN, whose relativistic jets point towards the Earth, i.e. blazars) suggests that the AGN impact their hosts (either by suppression or triggering of star formation) in a magnitude that is proportional to the jet power.

Until recently, powerful relativistic radio jets were virtually only found to be hosted in elliptical galaxies (e.g. Stickel et al. 1991; Kotilainen et al. 1998b,a; Scarpa et al. 2000; Urry et al. 2000; Kotilainen et al. 2005; Hyvönen et al. 2007; Olguín-Iglesias et al. 2016), which helped develop ideas on how jets, supermassive black holes and their host galaxies evolve. However, recently, a few studies report on blazar–like disc hosts, that is to say, with fully developed relativistic jets, capable of emitting γ–ray photons (Kotilainen et al. 2016; Olguín-Iglesias et al. 2017, and probably León Tavares et al. 2014). These blazar–like disc galaxies, constitute a peculiar type of AGN known as Narrow–line Seyfert 1s (NLSy1s), characterized by narrower Balmer lines full width at half maximum (FWHM(Hβ) < 2000 km s−1) than in normal Seyferts, flux ratios [OIII]/Hβ < 3, strong optical FeII lines (FeII bump) and a soft X-ray excess (Osterbrock & Pogge 1985; Orban de Xivry et al. 2011). Based on the full
width at half maximum (FWHM) of their Broad Line Region (BLR) lines and the continuum luminosity (Kaspi et al. 2000), their central black holes masses (MBH) are estimated to range from $\sim 10^6 M_\odot$ to $\sim 10^8 M_\odot$ (Mathur et al. 2012a) and thus, their accretion rates are thought to be close to the Eddington limit. A small fraction has been found to be radio loud (RL, 7%, Komossa et al. 2006) and among them, a smaller fraction (so far, 15 galaxies), are the above-mentioned γ-ray emitters NLSy1s (hereafter, γ-NLSy1s).

RL–NLSy1s (including γ–NLSy1s), are excellent laboratories to study the mechanisms that make AGN able to launch and collimate fully developed relativistic outflows at a likely early evolutionary stage. Thus, in this study, we characterize a sample of RL–NLSy1s (including 12 γ–NLSy1s detected so far) with the aim of determining the properties of their host galaxies that could shed some light on the necessary conditions and mechanisms to generate the relativistic jet phenomenon.

This paper is organized as follows. In Section 2, we present the sample and observations. In Section 3 we explain the data reduction and the methodology of the analysis. In Section 4 we discuss the results and compare them with previous studies. Finally, in Section 6, we summarize our findings. All quantitative values given in this paper are based on a cosmology with $H_0 = 70\text{km} s^{-1}\text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

3 DATA REDUCTION AND ANALYSIS

3.1 Data reduction

The images of the galaxies in the sample observed with the NOT were reduced using the NOTCam script for IRAF REDUCE. This script takes the consequitive dithered images, corrects for flatfield, interpolates over bad pixels, and makes a sky template that is subtracted from each image. The images are then registered based on interactively selected stars (and RA/DEC header keywords) and combined to obtain the final reduced image. For the images observed with the ISAAC a similar procedure was followed. A flat frame was derived from the twilight images and a sky image was obtained by median filtering the individual frames in the stack. The individual frames were then aligned using bright stars as reference points in the field and combined to produce the final reduced co-added image (see Olguín-Iglesias et al. 2016, for more details). The photometric calibration was performed by using the field stars in our images with the magnitudes reported by 2MASS (Skrutskie et al. 2006).

3.2 Photometric decomposition

The 2D light distribution of the reduced images is modeled using the image analysis algorithm GALFIT (Peng et al. 2011). The different components of a galaxy are described using different analytical functions. For bulges and possible bars in the host galaxies of the sample, we use the Sérsic profile, which functional form is:

$$\Sigma(r) = \Sigma_0 \exp \left( -\kappa \left( \frac{r}{r_e} \right)^{1/n} - 1 \right) \tag{1}$$

where $\Sigma_0$ is the surface brightness of the pixel in the effective radius ($r_e$, radius where half of the total flux is concentrated). The parameter $n$ (the Sérsic index) is often referred to as a concentration parameter and the variable $\kappa$ is coupled to it.

We also use the exponential function, since it describes well the radial behavior of galactic discs. Although, the exponential function is a special case of the Sérsic profile (when $n = 1$), nomenclature-wise, we use it when the component to fit is a disc, otherwise we use the Sérsic profile with $n = 1$. Its functional form is:

$$\Sigma(r) = \Sigma_0 \exp \left( -\frac{r}{r_s} \right) \tag{2}$$

where $\Sigma(r)$ is the surface brightness at a radius $r$, $\Sigma_0$ is the surface brightness at the center of the target and $r_s$ is the scale length of the disc.

The sky background is also modeled. We use a simple flat plane that can be tilted in x and y direction. Finally, the nuclear emission due to the powerful AGN of the galaxies of the sample is fitted using a modeled point spread function (PSF).

1 http://www.not.iac.es/instruments/notcam
3.2.1 PSF modeling

In most cases, the PSF modeling, only consists on subtracting a bright non-saturated star close to the target and removing its background. However, it is not always possible to get a suitable star in the field of view (FOV). In the case where only saturated or faint stars are found, the following procedure is implemented:

First, we identify the stars in the FOV. Then, we select, preferentially, the stars with no sources within ~7" radius and more than ~10" away from the border of the FOV. The selected stars are centered in 50"×50" boxes, where all extra sources are masked out by means of the segmentation image process of SExtractor (Bertin & Arnouts 1996).

The wings of the PSF are modeled by fitting a saturated star with a number of exponential and Gaussian functions (top panel Figure 1). The core of the PSF is modeled using another star (in this case, it is important not to be saturated) with Gaussian functions and the previously generated wings model (bottom panel Figure 1). The magnitude difference between the saturated and non-saturated stars is important, since there must be an overlap in order to match the wings and core models. The resultant model is tested by fitting random stars in the FOV.

In order to take into account the image PSF in the modeling of the galaxies, we convolved our PSF model with the real functional form of a given galaxy component leads to the errors in the galaxy modeling of the galaxies, we convolved our PSF model with the real functional form of a given galaxy component leads to the errors in the galaxy modulation. The uncertainties of this sample, is composed by the AGN.

3.2.2 Uncertainties

The uncertainties due to the PSF are accounted for by using different PSF models. A number of PSF models can be derived using different stars or different amount of Gaussians.

Table 1: Main properties of the RL–NLSy1s analysed in this work and observations log.
The simulated galaxies have a nuclear component, represented by a star within the FOV. They also have a Sérsic function, with $n = 1$, which represents a bulge and an exponential function representing a disc. The background is taken from the same image as the star of the nuclear component. Every galaxy in the simulation has a different combination of parameters (bulge, disc and nuclear signal to noise ratios; bulge effective radius and seeing). The simulated galaxies are modeled in an identical way to the real galaxies in our sample in order to find whether the quality in our images is good enough to allow an acceptable subtraction of parameters. We found that the ability to properly retrieve the parameters of the bulges, depend both on the size of the bulge, with respect to the seeing, and on the brightness of the bulge with respect to the brightness of the other components. In this way, the parameters of faint bulges (with respect to the nucleus) might be properly retrieved provided that they are large enough (e.g. simulation 42). We note that, although the parameters of a bulge might not be properly retrieved, it might still be detected, although with not enough quality to retrieve its parameters. This means that in some simulations, we were able to properly characterize the nucleus and disc and also detect a residual (unable to be fitted) that we knew, beforehand, it was the bulge (e.g. simulation 1, 6 and 57). We focus on the parameters of bulge and nucleus, although all our simulations include a disc, with the intention of studying the effect of this component on the fittings. Most of the time the disc is not bright enough to hamper the bulge fit. However, the brightness of the bulge and the nucleus can often be high enough to make the modeling and even detection of the disc difficult (e.g. simulations 29, 30 and 75).

In figure 2 we show the set of simulations in a plot of the ratio between the bulge and nucleus S/N versus bulge effective radius normalized to the seeing FWHM. We use signal-to-noise ratios instead of magnitudes because in our simulations we take into account the seeing. The blurring caused by seeing makes the signal of point sources smaller. It also spreads out the light from extended sources, which reduces the measured signal-to-noise and the ability of telescopes to see detail but does not affect the derived magnitudes. Hence, the same source observed with different settings have the same magnitude, but different signal-to-noise ratios, which is crucial in galaxy fitting. In our simulations, signal-to-noise ratios refer to the peak counts of the source divided by the background noise in the same region. We find the bulk of our sample in the region where the correctly retrieved simulated galaxies lie, which gives us confidence in the reliability of our analysis. We consider a model correct when the difference between a given parameter of the simulation and the same parameter of the model is less than the maximum error for such parameter in our analysis of the real galaxies sample (i.e. magnitude error $\Delta Mag_{err} \leq 0.50$, bulge effective radius error $Re_{err} \leq 100\%$ and Sérsic index error $n_{err} \leq 1.35$). Two galaxies in our sample lie outside that region (PMNJ0948+002 and J095820+322401), suggesting that those parameters are incorrectly retrieved, and hence left out of the analysis.

Figure 1. PSF modeling procedure. In top panel, we show the PSF wings modeling by fitting Gaussians and exponential functions to the surface brightness of a saturated star (Star 1). Since this star is saturated, there is no information on the PSF core. In bottom panel, we show the PSF core modeling by fitting a Gaussian function to the surface brightness of a non saturated star (star 2). As can be seen, one part of the wings in this star is under the detection limit (red horizontal segmented line) and another part is noisy, hence the need of the saturated star in order to derive the PSF wings.

and exponentials. The uncertainties due to the sky is derived by running several sky fits in separated regions of 300 pixels $\times$ 300 pixels in the FOV. The zeropoint magnitude depends on the star used to derive it, since they are estimated from the magnitudes of several stars (see Section 3.1) then, we use the zeropoint magnitude variations ($\sim \pm 0.1\text{mag}$) as another source of uncertainties.

Using these variations, GALFIT is run several times. The resultant fits are used to make a statistic where the best-fit value is the mean and the errors are $\pm 1\sigma$ for every parameter of the galaxy model.

3.3 Simulations

In order to assure the suitability of the images to resolve galaxy bulges, we performed a set of simulations (Table A1). The simulated galaxies have a nuclear component, represented by a star within the FOV. They also have a Sérsic function, with $n = 1$, which represents a bulge and an exponential function representing a disc. The background is taken from the same image as the star of the nuclear component. Every galaxy in the simulation has a different combination of parameters (bulge, disc and nuclear signal to noise ratios; bulge effective radius and seeing). The simulated galaxies are modeled in an identical way to the real galaxies in our sample in order to find whether the quality in our images is good enough to allow an acceptable subtraction of parameters. We found that the ability to properly retrieve the parameters of the bulges, depend both on the size of the bulge, with respect to the seeing, and on the brightness of the bulge with respect to the brightness of the other components. In this way, the parameters of faint bulges (with respect to the nucleus) might be properly retrieve provided that they are large enough (e.g. simulation 42). We note that, although the parameters of a bulge might not be properly retrieved, it might still be detected, although with not enough quality to retrieve its parameters. This means that in some simulations, we were able to properly characterize the nucleus and disc and also detect a residual (unable to be fitted) that we knew, beforehand, it was the bulge (e.g. simulation 1, 6 and 57). We focus on the parameters of bulge and nucleus, although all our simulations include a disc, with the intention of studying the effect of this component on the fittings. Most of the time the disc is not bright enough to hamper the bulge fit. However, the brightness of the bulge and the nucleus can often be high enough to make the modeling and even detection of the disc difficult (e.g. simulations 29, 30 and 75).

In figure 2 we show the set of simulations in a plot of the ratio between the bulge and nucleus S/N versus bulge effective radius normalized to the seeing FWHM. We use signal-to-noise ratios instead of magnitudes because in our simulations we take into account the seeing. The blurring caused by seeing makes the signal of point sources smaller. It also spreads out the light from extended sources, which reduces the measured signal-to-noise and the ability of telescopes to see detail but does not affect the derived magnitudes. Hence, the same source observed with different settings have the same magnitude, but different signal-to-noise ratios, which is crucial in galaxy fitting. In our simulations, signal-to-noise ratios refer to the peak counts of the source divided by the background noise in the same region. We find the bulk of our sample in the region where the correctly retrieved simulated galaxies lie, which gives us confidence in the reliability of our analysis. We consider a model correct when the difference between a given parameter of the simulation and the same parameter of the model is less than the maximum error for such parameter in our analysis of the real galaxies sample (i.e. magnitude error $\Delta Mag_{err} \leq 0.50$, bulge effective radius error $Re_{err} \leq 100\%$ and Sérsic index error $n_{err} \leq 1.35$). Two galaxies in our sample lie outside that region (PMNJ0948+002 and J095820+322401), suggesting that those parameters are incorrectly retrieved, and hence left out of the analysis.
4 THE HOST GALAXIES

In table 2, we show a summary of the NLSy1 host and nuclear properties derived from the two-dimensional surface brightness decomposition analysis. In the cases where the host galaxy is not detected we estimated upper limits for their magnitudes by simulating a galaxy (following the method from Kotilainen et al. 2007; Olguín-Iglesias et al. 2016), assuming an average effective radius and S´ersic index from the successfully detected hosts and then, increasing the magnitude until the component becomes detectable with a signal to noise ratio S/N=5, which by our own experience, is required in order to properly retrieve the structural parameters of the galaxy components.

In table 2, we summarize the nuclear and (disky-) bulge properties. However, in Appendix B1, the detailed fitting results are shown individually for every host in the sample. Out of the sample of 29 radio-loud NLSy1 host galaxies, 21 were successfully detected, 7 of which are γ-rays emitters and 14 are only radio-loud. For the sample, we estimate an average J-band absolute nuclear and host magnitudes of $M(J)_{\text{nuc}} = -23.8 \pm 1.7$ and $M(J)_{\text{bulge}} = -23.1 \pm 1.0$ and an average K-band absolute nuclear and host magnitudes of $M(K)_{\text{nuc}} = -25.6 \pm 1.4$ and $M(K)_{\text{bulge}} = -24.8 \pm 1.1$. The host luminosities for these galaxies are slightly fainter than elliptical galaxies hosting other types of radio–loud AGNs (e.g., Olguín-Iglesias et al. 2016, $M(K)_{\text{FSRQs}} = -26.2 \pm 0.9$ and $M(K)_{\text{LLBs}} = -22.0 \pm 1.0$).

![Figure 2](image.png)

**Figure 2.** Ratio of the bulge over nucleus S/N versus bulge effective radius normalised to the seeing FWHM. We see the location of the correctly retrieved simulated galaxies (green circles), the incorrectly retrieved simulated galaxies (red crosses) and the real galaxies in our sample (yellow stars, including all 18 galaxies with K–band observations from the NOTcam and fitted in this study, and excluding 4 galaxies from previous studies and/or observed with the ESO/ISAAC, 6 unresolved galaxies and 1 observed only in J–band) A limit that divides the correctly from incorrectly retrieved simulated galaxies is represented by a segmented line.

![Figure 3](image.png)

**Figure 3.** The Kormendy relation in K–band. Symbols are explained in the figure. The bulge effective radius ($\log R_e$) is plotted versus the surface brightness at that radius ($\mu_e$). A typical error bar is shown in the lower left corner. Overlaid are a sample of high–luminosity blazars (FSRQs) and low–luminosity blazars (BL Lacs objects) from Olguín-Iglesias et al. (2016), all of them hosted by giant elliptical galaxies. For the blazars sample, we show the 95 per cent prediction bands (dotted lines) and the best linear fit (black dashed line) relation. For the NLSy1s (the 20 detected galaxies in our sample with K–band observations. Missing are 2 with unreliable fittings, 6 undetected galaxies and 1 without K–band observations), we show the best linear fit (yellow dashed line). There are no NLSy1s inside the 95 per cent prediction bands of the Kormendy relation, suggesting that they are hosted by disc–like bulges. A cosmological surface brightness dimming correction of the form $(1 + z)^{-3}$ was applied to all targets (in this work and in Olguín-Iglesias et al. 2016).

$$M(K)_{\text{BLLacs}} = -25.6 \pm 0.6$$

and rather similar to those of an L* galaxy ($M(K) = -24.8 \pm 0.3$ Mobasher et al. 1993).

The average bulge effective radius for J-band and K-band respectively is $R_{eff} = 1.9 \pm 1.3$ kpc and $R_{eff} = 1.5 \pm 1.1$kpc and the average S´ersic index is $n = 1.2 \pm 0.4$ for J-band and $n = 1.3 \pm 0.3$ for K-band. The S´ersic index can be used as an approximation to classify bulges (either disky, $n < 2$ or classical, $n \geq 2$, Fisher & Drory 2008). According to the S´ersic index derived from the photometrical analysis (with the exception of J16410+3454 and J17221–5654, whose S´ersic index might be $n > 2$ given their uncertainties), all the NLSy1s hosts bulges are disc-like. However, it is well known that using the S´ersic index to discern between classical from disc–like bulges can generate many misclassifications (Gadotti 2009). To address this, we used the fact that disc–like and classical bulges are expected to be structurally different. Therefore, disc–like bulges should not follow the Kormendy relation (inverse relation between $\mu_e$ and $R_e$ found in elliptical galaxies and classical bulges; Kormendy 1977). In fact, Gadotti (2009) finds that disc-like bulges lie below the Kormendy relation and hence, it can be used to distinguish them from classical bulges.

In figure 3, we explore the Kormendy relation by plotting the effective radius ($R_e$) versus the surface brightness at the bulge effective radius ($\mu_e$) of the detected hosts with K–band observations 3. Together, we plot the results of the blazars hosts analysis from Olguín-Iglesias et al. (2016). The

3 In contrast to this work, the original Kormendy relation, uses the average surface brightness within the bulge effective radius.
blazars hosts show a statistically significant correlation between $R_e$ and $\mu_e$ (the Kormendy relation). On the other hand, the NLSy1s in the sample show a shallower trend. The 95% prediction bands of the correlation are represented by dotted lines. Since the aim of the prediction bands is to encompass the likely values of future observations from the same sampled population, we might say that it is most likely that the hosts that lie below the lower prediction band are not classical bulges. We can see that all (20 with host detections, K-band observations and inside the ‘correctly retrieved’ area) RL–NLSy1s lie below the Kormendy relation and below the 95% prediction bands. If errors are taken into account, 4 NLSy1s might be consistent with classical bulges and 16 are certainly disc–like bulges.

Although these results suggest disc–like systems as RL–NLSy1s hosts, some RL–NLSy1s might be hosted by classical–bulges. Therefore, further studies of their stellar populations and kinematics, using integral field spectroscopy (IFS), will help in understanding their nature. This result is not surprising, since the prevalence of disc–like bulges in this type of AGN hosts have been previously found (e.g. Orban de Xivry et al. 2011; Mathur et al. 2012b). However, very little is known about the presence of radio jets launched from disc galaxies galaxies. In the past, only a small number of disc–like systems were found to be radio galaxies (e.g. Ledlow et al. 1998; Hota et al. 2011; Morganti et al. 2011; Bagchi et al. 2014; Kaviraj et al. 2015; Mao et al. 2015; Singh et al. 2015). However, only three (included in this work) have been found to do, be $\gamma$–rays emitters (León Tavares et al. 2014; Kotilainen et al. 2016; Olguín–Iglesias et al. 2017, 1H0323+342,PKS2004-447, and FBQSJ1644+2619, respectively).

The uniqueness of the hosts of NLSy1s (and nearby environment), might hint at how these galaxies acquired such properties. Spiral arms, bar incidence, interactions evidence, etc., could shed some light on the fueling mechanisms needed by the central supermassive black hole to form and develop powerful relativistic jets. Therefore, in the following sections we discuss on the specific features that the hosts of the galaxies in the sample show.

4.1 Bar frequency

Through a simple visual inspection, some galaxies reveal the presence of a bar in their brightness distributions. However, in order to have a quantitative identification of these bars, we adopt an analysis based on the ellipse fit to the galaxy isophotes, where radial variations of ellipticity ($\epsilon$) and position angle (P.A.), exhibit the existence, ellipticity and extent of the bar. Moreover, some bars detected by this way, might not be obvious at a glance. The detection of bars using this method consists on finding a local maximum in $\epsilon$, which indicates the bar end. Along the bar, the P.A. should remain constant, thus along the suspected bar, the P.A. should not change much (typically $\Delta P.A. \lesssim 20^\circ$, Wozniak et al. 1995; Jogee et al. 1999; Menéndez-Delmestre et al. 2007). At larger radius, further away from the bar end, we should measure the ellipticity and P.A. of the disc then, the ellipticity should drop (at least $0.1; \Delta \epsilon \gtrsim 0.1$) and most likely the P.A. will change. In Appendix B2 we show the plots of P.A. and ellipticity versus radius of 10 of the galaxies that fulfill this criteria (the other two galaxies in the sample with detected bars are shown in Kotilainen et al. 2016; Olguín-Iglesias et al. 2017). Thus, the detected hosts with bars represent 52% (77% RL–NLSy1s and 20% $\gamma$–NLSy1s) of the galaxies in the sample, in comparison, Laurikainen et al. (2004) finds bars in 62%±9% of Seyfert galaxies. It must be stressed that, although near–IR imaging (specially K–band) provides a reliable assessment of the bar fraction, we might miss some bars given the relative high redshift of some of the galaxies in the sample (e.g. J1722+5654 is the galaxy with the highest redshift $z = 0.426$ and a bar detection).

In addition to finding bars, the radial variations of ellipticity and P.A., help in estimating their ellipticity and length. Ellipticity has been shown to be a good bar strength indicator (Laurikainen et al. 2002). Abraham & Merrifield (2000) defined a bar strength parameter given by

$$f_{bar} = \frac{2}{\pi} \arctan((1-\epsilon_{bar}^{-1/2}) - \arctan(1-\epsilon_{bar}^{-1/2}),$$

where $\epsilon_{bar}$ is the bar ellipticity at the bar end. Using this parameter, we find that, for our sample, $f_{bar} = 0.13 \pm 0.06$. By comparing this value with the findings of Laurikainen et al. 2007 (average $f_{bar} = 0.20 \pm 0.03$, from 216 galaxies observed in the NIR, including all Hubble types), we note that the bar strengths for our NLSy1s sample is rather low. By contrast, we find that the average bar length of our sample ($l_{bar} = 9.8$kpc $\pm 1.8$) is large when compared either with late type galaxies or early type galaxies ($\sim 0.5$ – 3.5kpc and $\sim 1$ – 10kpc, respectively; Erwin 2005). We note that, even if we assume that the galaxies with no bars detected in our sample have the shortest bars (0.5 kpc), the average bar length would be 5.9 kpc, still larger than the average for late type galaxies (2 kpc), early type galaxies (5.5 kpc) or both early and late type galaxies (3.75 kpc). These results might hint to the necessary conditions to properly channel the fuel towards the center of the galaxy to feed the black hole and trigger its activity. According to bar models by Athanassoula (1992), weak bars promote the inflow of gas toward the inner Lindblad resonance (ILR), and forms a nuclear ring. As long as the bar pattern speed remains low, the ILR is kept, which occurs provided that bars are long. If dynamical instabilities via gradual build-up of material show, material from that nuclear ring would flow inward and trigger the black hole activity, as hypothesize by Laurikainen et al. (2002). Low and steady evolution (secular evolution) might, thus, be capable of producing AGN as powerful as to launch radio jets.

4.2 Mergers and galaxy interactions

Secular evolution driven by stellar asymmetries (i.e. bars, lopsidedness, spiral patterns and other coherent structures) can be strengthened by external processes such as tidal interactions and mergers (Mapelli et al. 2008; Reichard et al. 2009). In our sample, 62% of the galaxies show some sign of merger, interaction or off centered components (9 $\gamma$–NLSy1s and 9 RL–NLSy1s, including both detected and not detected hosts). This result is important since both, observations and simulations suggest that AGN activity is closely related to galaxy interactions and mergers (e.g., Di Matteo et al. 2003;
The disc-like host galaxies of RL NLSy1s

Ellison et al. 2011; Silverman et al. 2011; Koss et al. 2012; Ellison et al. 2013; Capelo et al. 2015.

Particularly, in the case of the γ-NLSy1s, we note that only 3 out of 12 γ-NLSy1s do not show signs of interactions (PMN J0948+0022, z = 0.986; 4C+04.42, z = 0.996 and B3 1411+476, z = 0.705), considering their high redshift and that only one of these hosts is detected. The large fraction of interactions in the γ-NLSy1s of the sample (75% against 53%, when compared with RL-NLSy1s), largely consist of the host itself and another, significantly smaller, faint tidal feature (i.e. minor mergers; however, spectroscopic data is required to confirm the idea of these features as interactions).

This result is important since simulations (e.g. Qu et al. 2011) show that the angular momentum decreases more significantly when the stellar disc undergoes a minor merger than when it evolves in isolation. Hence, the difference in power between RL-NLSy1s and γ-NLSy1s, might thus be the result of the difference between the processes that drive their evolution. In this way, our findings suggest secular evolution as a process capable of producing, not only radio, but also γ-ray emitting jets.

Another important finding in our study is that, not only discs might be off-centered with respect to the nucleus, also some bulges might. This behavior has not only been predicted by simulations (Hopkins et al. 2012) but also previously observed. The first offset AGN reported was the Seyfert 1 galaxy NGC 3227 (Mediavilla & Arribas 1993), where the region of broad emission lines is offset from the kinematic center by ∼0.250 kpc. Another important example is the low-luminosity AGN NGC 3115 (Menezes et al. 2014), with an AGN located at a projected distance of ∼0.014 kpc from the stellar bulge. Similarly, using GAL-

Table 2: Parameters of the host galaxies of the RL NLSy1s sample derived from GALFIT 2D analysis. All K-corrections were performed using the K-corrections calculator (Chilingarian et al. 2010; Chilingarian & Zolotukhin 2012).
4.2.1 Notes on individual galaxies

Here, we provide a short description of the characteristics that each interacting galaxy shows (for images, see Appendix B1).

- J1032+342. The closest γ-ray emitter NLSy1 galaxy. In this galaxy a ringed structure is seen which is interpreted as “suggestive evidence for a recent violent dynamical interaction” by León Tavares et al. (2014), where an extensive discussion on these features is found on Olguín-Iglesias (2016).

- B2 1546+35A. When the host is decomposed into bulge and disc, the different parts are off centered with respect to each other. While the host galaxy image, both in J- and K-bands, looks similar, when it is represented using its surface brightness profile, the two bands differ.

- RXSJ1633+4718. Two disc galaxies interacting. Seemingly, the companion is also face-on. Again, the host galaxy shows a greater effect of the interaction on one of the bands. While in K-band, the bulge seems a bit off centered, in the J-band, both the disc and the bulge shows greater impact caused by an interaction.

- PKS1502+036. A clear companion only visible in J-band. The companion seems close, however, this galaxy does not show asymmetries as others in the sample. Although D’Ammando et al. (2018) finds it hosted in an elliptical galaxy, we find a better fit using a disc–like host.

- SBS1517+520. In this galaxy, the asymmetry of its surface brightness profile and its off centered disc (more evident in the K-band), hint towards some type of disruption induced by an interaction.

- FBQS J1102+2239. This galaxy represents a classical encounter between two disc galaxies. Very similar both in J- and K-bands, a remnant of the disc is detected in the AGN host. The companion keeps an spiral arm and it is barely connected with the main AGN host. Another blob is observed, an HH region, which is part of the system (according to optical spectra).

- IRAS 14506+5919. The AGN host is modeled using a disc–like bulge and an exponential disc. It shows a close and faint feature which is fitted using an exponential disc.

- J142106+38552. The host galaxy of this γ–NLSy1 was modeled using a bulge and a disc. In the image, a faint tail–like feature (which was not modeled due to its intensity) is observed. Suggestion of an interaction are observed in its off–centered disc.

- RXSJ1633+4718. Two disc galaxies interacting. Seemingly, the companion is also face-on. Again, the host galaxy shows a greater effect of the interaction on one of the bands. While in K-band, the bulge seems a bit off centered, in the J-band, both the disc and the bulge shows greater impact on its morphology.

- J16410+3454. This galaxy shows a feature that emerges after the fitting of a bulge+disc+AGN model. This additional component is modeled using a Sérsic profile with n \approx 1. The main disc seems off centered in the radial profiles (maybe because of the effect of the interaction).

- FBQS J1644+2619. In J–band, a ring feature shows, whose formation process might be that described by Athanassoula et al. (1997) and that PKS 2004-447 might be undergoing. Besides, a faint disruption of the ring suggests an interaction. On the other hand, in K–band, a bar is observed and the ring features is almost absent. An extensive discussion on these features is found on Olguín-Iglesias et al. (2016).
Table 4: Average $J-K$ colours for the bulge, disc and nucleus of the host galaxies in the sample.

| Subsample | $(J-K)_{\text{Bulge}}$ | $(J-K)_{\text{Disc}}$ | $(J-K)_{\text{Nuclear}}$ |
|-----------|------------------------|-----------------------|--------------------------|
| All       | 1.7 ± 0.7              | 1.7 ± 0.5             | 2.0 ± 0.5                |
| RL–NLSy1s | 1.5 ± 0.5              | 1.6 ± 0.6             | 2.0 ± 0.5                |
| γ–NLSy1s  | 2.1 ± 0.5              | 1.8 ± 0.4             | 1.9 ± 0.5                |

4.3 AGN, bulge and disc (J-K) colours

Table 4 shows the average J-K colours of the main components of the host galaxies in the sample (whenever they have both, J- and K-band information). We see that the disc and nuclear J-K colours remain virtually unchanged whether the subsample includes γ–NLSy1s or only RL–NLSy1s. We also note that, unexpectedly, bulge and disc colors for RL–NLSy1s are the same within errors (i.e. bulges are as blue as discs, when disc are expected to be bluer, Moriondo et al. 1998; Seigar & James 1998). This result is thus consistent with star-forming bulges, which imply large gas reservoirs.

On the other hand, the average J-K bulge colour changes depending on the subsample, being redder for γ–NLSy1s ($J-K = 2.1 ± 0.5$). According to findings by Glass & Moorwood (1985); Seigar & James (1998), NIR colours $J-K = 2.0$, could be the result of a dust-embedded AGN or a nuclear starbursts (if the component is extended, i.e. in bulges). Bulge reddening might be linked to the large fraction of γ–NLSy1s showing signs of minor mergers. Thus, according to these results, interactions are likely to play an important role in the nuclear activity of the galaxies in our sample.

5 AGN-HOST CONNECTION

In figure 4, we explore the $M_{K,\text{nuclear}} - M_{K,\text{bulge}}$ plot for our sample. The first thing we notice is that most of the sample data points fall in the bottom left corner, where high luminosity blazars (HLB), i.e. FSRQs and low luminosity blazars (LLB), i.e. BL Lacs coincide. However, three γ–NLSy1s (only one with host galaxy detection) are brighter and lie ~ 3mag apart from the group and two (also γ–NLSy1s) are fainter and lie ~ 1mag apart. At first glance the bulk of RL–NLSy1s, are part of either HLB or LLB. A further analysis shows that, if we include the NLSy1s in the HLB sample, the best linear fit marginally lies inside the 99% confidence intervals of the FSRQs best linear fit. There is a statistically significant positive correlation for the FSRQs sample ($r = 0.8$, $p = 4 × 10^{-12}$) which is kept virtually unchanged ($p = 10^{-12}$) when the RL–NLSy1s are added to the FSRQs.

When we analyze the NLSy1 sample alone, a statistically significant positive correlation is observed ($r = 0.6$, $p = 1 × 10^{-3}$). Whether the NLSy1 sample belongs to the FSRQs sample or not, its positive trend suggests that their jets also stimulate starburst activity in their hosts.

The results presented above suggest either FSRQs and RL–NLSy1s accretion modes locate them close to each other in the $M_{K,\text{nuclear}} - M_{K,\text{bulge}}$ plot. Bearing in mind that both, FSRQs and NLSy1s, are thought to accrete matter very efficiently via accretion discs, this is expected.

In order to rule out the scenario where RL–NLSy1s behave as LLB/BL Lacs (since, independently of nuclear magnitude, BL Lacs show a narrow range of bulge magnitudes, where the bulk of RL–NLSy1s bulge magnitudes also reside), we perform a two-dimensional Kolmogorov-Smirnov test for the bulge and nuclear magnitudes of BL Lacs and RL–NLSy1s. According to the results of this test ($p = 3.0^{-4}$) there is a statistically significant difference between the samples, suggesting that, in the $M_{K,\text{nuclear}} - M_{K,\text{bulge}}$ plot, BL Lacs and RL–NLSy1s are not similar.

Previous studies, conducted to RL–NLSy1s, had already supported the idea that, when compared with blazars, RL–NLSy1s are particularly similar to FSRQs (e.g. Paliya et al. 2013; Foschini et al. 2015; Paliya & Stalnin 2016). Provided that RL–NLSy1s are hosted by spiral galaxies, what our findings suggest, might be a substantive contribution since blazars are known to be hosted by elliptical galaxies and powered by massive black holes.

The positive trend in the NLSy1s and FSRQs samples clearly suggest a positive feedback scenario. The AGN outflows can induce star formation, both in the galactic disc through compression of molecular clouds Silk (2013) or directly in the outflowing gas Ishibashi & Fabian (2012).

6 SUMMARY

We have presented near–infrared images of a sample of 29 radio–loud NLS1 host galaxies, 12 of which are also classified as γ–NLSy1s. By thoroughly analyzing their 2D surface brightness distribution, we successfully detected 21 hosts (14 RL–NLSy1s and 7 γ–NLSy1s). Our near–infrared study allowed us to compare the photometrical properties of RL–NLSy1s with another type of AGN capable of launching powerful radio jets, namely blazars (both BL Lacs and FSRQs). The main findings of our study are summarized below.

- The photometrical properties derived by our 2D analysis for a sample of RL–NLSy1s suggests that, consistent with radio–quiet NLS1s and opposite to the jet paradigm, powerful relativistic jets can be launched from disc–like systems instead of elliptical galaxies or classical bulges.
- Secular evolution driven by the peculiar bar properties...
in our sample (long and weak) might be responsible for channeling fuel towards the center of the galaxy to feed the black hole and trigger the nuclear activity, whereas the nuclear activity in γ–NLSy1s could be the result of a similar process enhanced by minor mergers.

• RL–NLSy1s bulges and discs show the same average NIR colour \((J - K)_{\text{Disc}} = 1.6 \pm 0.6\) and \((J - K)_{\text{bulge}} = 1.5 \pm 0.5\). Since discs are expected to be bluer, this result is consistent with star–forming bulges, suggesting large gas reservoirs. On the other hand, γ–NLSy1s bulges show an average NIR colour \((J - K)_{\text{AGN}} = 2.1 \pm 0.5\). This reddening (with respect to RL–NLSy1s) suggests a nuclear starbursts, probably, linked to the large fraction of minor mergers shown by γ–NLSy1s, which in turn, could make a difference between RL– and γ–NLSy1s nuclear activity.

• We have discovered 6 systems showing an offset stellar bulge with respect to the AGN (with separations \(\Delta < 1.5\) kpc). This might be the result of a galaxy merger, strongly suggesting an important connection between AGNs and galaxy mergers.

• Hints of positive feedback are suggested when we plot \(M_{K,\text{nuclear}}\) versus \(M_{K,\text{bulge}}\) of the sample. We find that RL–NLSy1s behave in a similar manner as FSRQs (or high luminosity blazars), which might be the result of a similar accretion mode between RL–NLSy1s and FSRQs.

ACKNOWLEDGEMENTS

This work was supported by CONACyT research grant 280789 (México). JK acknowledges financial support from the Academy of Finland, grant 311438.

REFERENCES

Abdo A. A., et al., 2009a, ApJ, 699, 976
Abdo A. A., et al., 2009b, ApJ, 707, L142
Abraham R. G., Merrifield M. R., 2000, AJ, 120, 2835
Athanassoula E., 1992, MNRAS, 259, 345
Athanassoula E., Puerari I., Bosma A., 1997, MNRAS, 286, 284
Bagchi J., et al., 2014, ApJ, 788, 174
Bertin E., Arnouts S., 1996, A&ASS, 117, 393
Blecha L., Loeb A., 2008, MNRAS, 390, 1311
Blecha L., Brusken W., Burke-Spolaor S., Civano F., Comerford J., Darling J., Lazio T. J. W., Maccarone T. J., 2019, Astro2020: Decadal Survey on Astronomy and Astrophysics, 2020, 318
Capelo P. R., Volonteri M., Dotti M., Bellovary J. M., Mayer L., Governato F., 2015, MNRAS, 447, 2123
Chilingarian I. V., Zolotukhin I. Y., 2012, MNRAS, 419, 1727
Chilingarian I. V., Melchior A.-L., Zolotukhin I. Y., 2010, MNRAS, 405, 1409
Comerford J. M., Pooley D., Barrows R. S., Greene J. E., Zakamska N. L., Madejski G. M., Cooper M. C., 2015, ApJ, 806, 219

Figure 4. Plot of the nuclear K-band magnitude versus the bulge K-band magnitude for the host galaxies of the sample. Symbols are explained in the figure. Upper limits for unresolved galaxies are shown as down arrows. We show the 25 detected and undetected galaxies in our sample with K–band observations. Missing are 2 with unreliable fittings and 2 without K–band observations. Overlayed is a sample of blazars from Olguín-Iglesias et al. (2016), where the galaxies were analysed in K–band. For the blazars sample we show the best linear fits (dashed blue line for FSRQs and dashed red line for BL Lacs) and the 95 per cent prediction bands (dotted black lines). The 99 per cent confidence intervals are shown for FSRQs (blue shade) and NLSy1s (yellow shade). For the NLSy1s sample we show the best linear fit (green solid line). All K–A correction were performed using the K–corrections calculator (Chilingarian et al. 2010; Chilingarian & Zolotukhin 2012)
### Table A1: Parameters of the sample of simulated galaxies (columns 2-6) and the retrieved parameters of the simulated galaxies when they are modeled in an identical way to the real galaxies in our sample (columns 7-12).

| Simulation parameters (arcsec) | Retrieved parameters (arcsec) | Model quality |
|-------------------------------|-------------------------------|---------------|
| Seeing                        | m\text{bulge} | m\text{nuclear} | R\text{e bulge} | n | m\text{disc} | R\text{s disc} | |
| 1.60 15.00 18.50 0.10 15.00 | 15.90 20.75 2.13 0.06 15.09 2.83 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 14.85 19.63 2.09 0.19 15.09 2.87 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 12.66 17.92 2.14 0.84 15.09 2.75 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 11.64 13.54 2.05 0.06 15.09 2.81 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 11.64 13.54 2.05 0.06 15.09 2.81 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 14.85 19.63 2.09 0.19 15.09 2.87 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 12.66 17.92 2.14 0.84 15.09 2.75 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 11.64 13.54 2.05 0.06 15.09 2.81 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 14.85 19.63 2.09 0.19 15.09 2.87 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 12.66 17.92 2.14 0.84 15.09 2.75 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 11.64 13.54 2.05 0.06 15.09 2.81 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 14.85 19.63 2.09 0.19 15.09 2.87 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 12.66 17.92 2.14 0.84 15.09 2.75 | bad |
| 1.60 15.00 15.00 0.10 15.00 | 11.64 13.54 2.05 0.06 15.09 2.81 | bad |

Column (1) gives the simulation number; (2) the simulation seeing; (3) and (4) the simulated nuclear and bulge magnitudes; (5) the simulated bulge effective radius; (6) the simulated disc magnitude; (7) the modeled nuclear magnitude; (8) the modeled bulge magnitude; (9) the modeled bulge effective radius; (10) the modeled bulge Sersic index (11) the modeled disc magnitude; (12) the modeled disc scale length; (13) the quality with which the simulation was modeled.

The ‘**’ symbol shows a physically improbable parameter.

All the simulated galaxies have bulges with Sersic indexes (n=1) and discs with scale lengths (R_s = 3.0 arcsec).
The disc–like host galaxies of RL NLSy1s

| Simulation parameters | Retrieved parameters |
|-----------------------|----------------------|
| Seeing | $m_{\text{nuclear}}$ | $m_{\text{bulge}}$ | $R_e$ | $n$ | $m_{\text{disc}}$ | $R_s$ | Model quality |
| **Column (1) gives the simulation number; (2) the simulation seeing; (3) and (4) the simulated nuclear and bulge magnitudes; (5) the simulated bulge effective radius; (6) the simulated disc magnitude; (7) the modeled nuclear magnitude; (8) the modeled bulge magnitude; (9) the modeled bulge effective radius; (10) the modeled bulge S´ersic index (11) the modeled disc magnitude; (12) the modeled disc scale length; (13) the quality with which the simulation was modeled. The '**' symbol shows a physically improbable parameter. All the simulated galaxies have bulges with S´ersic indexes ($n=1$) and discs with scale lengths ($R_s = 3.0$ arcsec).**
APPENDIX B: MORPHOLOGICAL ANALYSIS

B1 Models
**Figure B1.** Surface brightness profile decomposition of the host galaxies in the sample. Top left: Shows the observed image. Top middle: Shows the image of the model used to describe the surface brightness distribution. Top right: Shows the residual image. Middle: Radial profile of the surface brightness distribution. The symbols and the main parameters of the models are explained in the plots. For the complete Appendix see the online material. Bottom: Residuals.
B2 Bar test

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.
Figure B2. Radial variation of ellipticity $\epsilon$ (blue circles) and of position angle PA (red squares) derived by ellipse fitting to the galaxy isophotes. Only the host galaxies that fulfill the criteria to identify bars are shown (see Section 4.1). For the complete Appendix see the online material.