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NARROW-LINE SEYFERT 1 GALAXIES

S. Komossa[1]

RESUMEN

Presento una revisión breve de las propiedades conocidas de las galaxias Seyfert 1 con líneas angostas (NLS1) en todo el espectro electromagnético y de los modelos propuestos para explicarlas. Sus propiedades de continuo y de emisión de líneas manifiestan una forma extrema de la actividad Seyfert. Las galaxias NLS1 en sí pueden ofrecer pistas importantes para discernir los parámetros que impulsan la actividad nuclear. Sus tasas de acreción altas y cercanas a la tasa de Eddington proveen una nueva visión de la física de acreción; sus bajas masas de agujeros negros y sus posibles edades jóvenes permiten atacar problemas tales como el crecimiento de agujeros negros; la fuerte emisión del Fe II restringe fuertemente al propio Fe II y a los modelos de formación de metales, así como a las condiciones físicas de estas nubes de emisión; además su emisión callada en radio nos permite volver a explorar las causas de la emisión en radio fuerte y la bimodalidad de los AGN en objetos radio callados y radio fuertes.

ABSTRACT

I provide a short review of the properties of Narrow-line Seyfert 1 (NLS1) galaxies across the electromagnetic spectrum and of the models to explain them. Their continuum and emission-line properties manifest one extreme form of Seyfert activity. As such, NLS1 galaxies may hold important clues to the key parameters that drive nuclear activity. Their high accretion rates close to the Eddington rate provide new insight into accretion physics, their low black hole masses and perhaps young ages allow us to address issues of black hole growth, their strong optical Fe II emission places strong constraints on Fe II and perhaps metal formation models and physical conditions in these emission-line clouds, and their enhanced radio quiteness permits a fresh look at causes of radio loudness and the radio-loud radio-quiet bimodality in AGN.

Key Words: galaxies: active — galaxies: Seyfert

1. INTRODUCTION

Narrow-line Seyfert 1 galaxies are a subclass of active galactic nuclei (AGN). Their spectra exhibit exceptional emission-line and continuum properties. The most common NLS1 defining criterion is the width of the broad component of their optical Balmer emission lines in combination with the relative weakness of the [O III]λ5007 emission ($\mathrm{FWHM_{H\beta}} < 2000$ km s^{-1} and [O III]/$\mathrm{H\beta_{totl}} < 3$; Osterbrock & Pogge 1985; Goodrich 1989)[2]. NLS1 galaxies typically show strong Fe II emission which anticorrelates in strength with the [O III] emission, and with the width of the broad Balmer lines. Often the presence of Fe II emission is added as further NLS1 classification criterion, and Veron et al. (2001) suggest the use of an intensity ratio Fe II/$\mathrm{H\beta_{totl}} >$ 0.5.

NLS1 galaxies as AGN with the smallest Balmer lines from the Broad Line Region (BLR) and the strongest Fe II emission, cluster at one extreme end of AGN correlation space. It is expected that such correlations provide some of the strongest constraints on, and new insights in, the physical conditions in the centers of AGN and the prime drivers of activity, and the study of NLS1 galaxies is therefore of particular interest. For instance, observations and interpretations hint at smaller black hole masses in NLS1 galaxies, and as such their black holes represent an important link with the elusive intermediate mass black holes, which have been little studied so far. Accreting likely at very close to the maximum allowed values, NLS1 galaxies are important testbeds of accretion models.

This paper provides a short overview of the multiwavelength properties of NLS1 galaxies and major models to explain them.

[1]Max-Planck-Institut fuer extraterrestrische Physik, Giessenbachstrasse 1, 85748 Garching, Germany (skomossa @mpe.mpg.de).

[2]While it is clear that a strict cutoff in line width ($\mathrm{FWHM_{H\beta}} < 2000$ km s^{-1}) is a gross simplification of any classification scheme, this historical value is still most commonly adopted for practical purposes. Suggestions have been made that more advanced NLS1 classification schemes would, for instance, incorporate the source luminosity (e.g., Laor 2000; Veron-Cetty et al. 2001). According to Sulentic et al. (2008, and references therein), AGN properties appear to change more significantly at a broad line width of $\mathrm{FWHM_{H\beta}} \approx 4000$ km s^{-1}.

2. EMISSION-LINE AND CONTINUUM PROPERTIES

2.1. *Multi-wavelength continuum and emission lines: trends and correlations*

Correlations among AGN properties provide insight into the underlying drivers and therefore enrich our understanding of the physics and evolution of AGN. A commonly applied method aimed at identifying the strongest correlations and the underlying parameters, is the Principle Component Analysis (e.g., Boroson 2004). Applied to NLS1 and BLS1 galaxies, the strongest correlations involve the width of the Hβ line and the strength of the [O III] line and of the Fe II complex (e.g. Boroson & Green 1992; Sulentic et al. 2000, 2002, 2008; Boroson 2002). NLS1 galaxies show, on average, the smallest Balmer lines, strongest Fe II emission, and smallest ratios of [O III]/H$\beta_{\rm totl}$.

Additional emission line trends across the NLS1-BLS1 galaxy population include stronger [O III] line complexity (blueshifts) of NLS1 galaxies (e.g., Zamanov et al. 2002; Bian et al. 2005; Boroson 2005), stronger C IV blueshifts/asymmetries (e.g., Sulentic et al. 2000, 2007; Wills et al. 2000; Leighly & Moore 2004), smaller ratios of C IV/Lyα (e.g., Wills et al. 2000; Kuraszkiewicz et al. 2000), and, on average, higher intensity ratios of [S II]6716/6731 corresponding to lower densities of their narrow-line regions (NLRs; Xu et al. 2007)[3]. In the NIR, NLS1 galaxies show higher line ratios between coronal lines and low-ionization forbidden lines than BLS1 galaxies (Rodriguez-Ardila et al. 2002).

In comparison with BLAGN, NLS1 galaxies are less often very radio-loud (Komossa et al. 2006), tend to be overluminous in the infrared (Moran et al. 1996; Ryan et al. 2007), underluminous/redder in the ultraviolett (Rodriguez-Pascual et al. 1997; Constantin & Shields 2003), and show a much larger scatter in X-ray spectral slopes with, on average, steeper soft and slightly steeper hard X-ray spectra (e.g., Puchnarewicz et al. 1992; Wang et al. 1996; Grupe 1996; Boller et al. 1996; Brandt et al. 1997; Leighly 1999; Comastri 2000; Vaughan et al. 2001; Grupe 2004; Zhou et al. 2006; see Williams et al. 2004 for a subsample of NLS1 galaxies with relatively flat X-ray spectra). NLS1 galaxies vary in a similar way as BLS1 galaxies in the optical regime (Klimek et al. 2006), perhaps even less than BLS1s (Ai et al. 2008; Giannuzzo et al. 1998). Long-term optical monitoring (several decades) of a few NLS1 galaxies revealed variability by 0.5–1 mag on time scales as short as several days (Greiner et al. 1996). A similar coverage is needed for much larger samples. On the other hand, NLS1 galaxies vary more than BLS1s in the X-ray regime (e.g., Leighly 1999; Grupe 2004; McHardy et al. 2006).

Apart from thorough work on optical emission-line spectroscopy[4], NLS1 galaxies have been studied in greatest detail in X-rays. They show, on average, steeper X-ray spectra than BLS1 galaxies, even though the scatter is very large. Their X-ray spectra are complex and evidence for cold and ionized absorption, partial covering, and reflection components has been presented (e.g., Wang et al. 1996; Komossa & Meerschweinchen 2000; Crummy et al. 2006; Chevalier et al. 2006; Gallo 2006; Done et al. 2007; Grupe et al. 2007c). Which emission/absorption mechanisms dominate on average is still being investigated.

2.2. *Frequency of NLS1 galaxies*

The observed fraction of NLS1 galaxies among AGN is a function of wavelength band and luminosity; large samples free of selection biases are still needed. Soft X-ray selection turned out to be quite efficient in identifying NLS1 galaxies, and Grupe (2004) reported a fraction of 46% NLS1 galaxies among his bright, soft X-ray selected broad-line AGN sample. On the other hand, the fraction of NLS1 galaxies in other ROSAT X-ray samples was significantly lower, and Hasinger et al. (2000) found only 1 NLS1 galaxy out of 69 AGN identified in a ROSAT deep field. The fraction of NLS1 (vs. BLS1) galaxies in predominantly optically selected samples is typically ∼15%, but may increase in dependence of luminosity (up to ∼20%; Zhou et al. 2006).

2.3. *NLS1 models.*

A number of scenarios have been considered in order to explain the observed correlations and trends in multi-wavelength NLS1 parameter space. These include: Accretion rates close to or even super-Eddington and low black hole masses (see §§ 3 and 4), winds and density effects (e.g., Lawrence et al. 1997; Gaskell 2000; Wills et al. 2000; Bachev et al. 2004; Xu et al. 2003, 2007), metallicity (e.g., Mathur 2000; Shemmer & Netzer 2002; Nagao et al. 2002;

[3]See Marziani et al. (2006), Sulentic et al. (2008) for reviews, and Zhou et al. (2006) for correlation analysis and multi-wavelength trends of the largest NLS1 sample to date, selected from the SDSS. It has to be noted that several of the multi-wavelength trends mentioned in this section are based on relatively small samples, sometimes as small as ∼5 objects.

[4]Among NLS1 galaxies, the prototype I Zw 1 may have the best studied optical spectrum - see the detailed work by Veron-Cetty et al. (2004).

Warner et al. 2004; Shemmer et al. 2004; Fields et al. 2005), and ionized absorption (e.g., Komossa & Meerschweinchen 2000; Gierlinski & Done 2004; Done et al. 2007). While there is no space here to review all of these in detail, I will summarize briefly some of the major models and potential key parameters.

3. BLACK HOLE MASSES

Several lines of evidence hint at small black hole masses in NLS1 galaxies as a class. There are different ways of determining black hole masses of AGN in general, and of NLS1 galaxies in particular. The method most commonly applied to BLAGN is the relation between BLR radius and black hole mass, based on reverberation mapping results for Seyfert galaxies (e.g., Peterson et al. 2004; Kaspi et al. 2005). Few NLS1 galaxies have been reverberation-mapped so far (Peterson et al. 2000), so an assumption often made is that the relation obtained for BLS1 galaxies also applies to NLS1s. Most studies applying the mass-radius relation, and variants of it, find systematically lower black hole masses in NLS1 galaxies than in BLS1s (e.g., Boroson 2002; Grupe & Mathur 2004; Collin & Kawaguchi 2004; Mathur & Grupe 2005a,b; Komossa & Xu 2007). Attempts to correct for possible inclination effects (§ 6) and/or measurements of the 'second moment' of the Hβ line, point to possibly higher black hole masses (Collin et al. 2006; Watson et al. 2007), but still off-set from the bulk of the BLS1 population.

Independent evidence for small black hole masses of NLS1 galaxies comes from X-ray observations, particularly variability studies (e.g., Hayashida 2000; McHardy et al. 2006; Zhou et al. 2007b), and is based on an observed anti-correlation between variability time scale and black hole mass (e.g., Papadakis 2004). In a few cases, low black hole masses have been measured from stellar velocity dispersion (Barth et al. 2005) and bulge luminosity (Botte et al. 2004).

4. ACCRETION RATES

Closely linked to (the correctness of estimates of) black hole masses is the accretion rate relative to the Eddington rate, generally parameterized as ratio of $L_{\rm bol}/L_{\rm Edd}$, where the bolometric luminosity $L_{\rm bol}$ is estimated in most cases from measurements in a single energy band plus a fixed bolometric correction, and $L_{\rm Edd} = 1.3\,10^{38} M/M_{\odot}$. Early suggestions that NLS1 galaxies might accrete close to the Eddington rate (Boroson & Green 1992), were bolstered by more recent studies, theoretical considerations, and by estimates of black hole masses from optical emission-line and continuum measurements (e.g., Wang et al. 1996; Boller et al. 1996; Laor et al. 1997; Mineshige et al. 2000; Sulentic et al. 2000; Nicastro 2000; Collin & Huré 2001; Marziani et al. 2001; Boroson 2002; Kawaguchi 2003; Xu et al. 2003; Czerny et al. 2003; Collin & Kawaguchi 2004; Grupe 2004; Bachev et al. 2004; Warner et al. 2004; Tanaka et al. 2005; Collin et al. 2006; Xu et al. 2007). Independently, the shape and luminosity of the soft and hard X-ray spectrum was used to argue for accretion close to the Eddington rate, or even super-Eddington (e.g., Pounds et al. 1995; Kuraszkiewicz et al. 2000; Wang & Netzer 2003)[5]. In the Eigenvector (EV) analysis of Boroson (2002), $L_{\rm bol}/L_{\rm Edd}$ drives EV1, while accretion rate drives EV2.

5. WINDS AND OUTFLOWS

Accretion close to the Eddington rate implies the presence of strong radiation-pressure driven outflows in NLS1 galaxies. Circumstancial evidence for outflows in NLS1 galaxies on the scales of their emission line regions comes from blue asymmetries and shifts of spectral lines (e.g., Sulentic 2000, 2007; Xu et al. 2003; Leighly & Moore 2004; Boroson 2005; Baskin & Laor 2005; Bian et al. 2005; Aoki et al. 2005). Lawrence et al. (1997) speculated that the density of an outflowing wind could be among the primary drivers of NLS1 properties. Indeed, Xu et al. (2007) find that the average density of the NLR of NLS1 galaxies is lower than that of BLS1 galaxies, and that NLR density is correlated with the blueshift of the blue wing of the [O III] emission line.

6. INCLINATION

The question whether NLS1 galaxies are seen at preferred viewing angles –closer to pole-on– and whether this effect could contribute to, or dominate, their extreme properties has been discussed ever since their discovery (e.g., Osterbrock & Pogge 1985; Puchnarewicz et al. 1992; Collin & Kawaguchi 2004). Several lines of arguments have been presented that orientation is not the dominant effect, for instance because [O III] luminosity was involved in key correlations (Boroson & Green 1992) and is believed to be an isotropic property. Smith et al. (2002, 2004) have shown that polarization properties of NLS1 and BLS1 galaxies are similar and argued against a pole-on orientation of NLS1 galaxies. On the other hand, there are some lines of evidence that

[5]Note that Williams et al. (2004) report a correlation between $L_{\rm 1keV}/L_{\rm Edd}$ and X-ray powerlaw index in the sense that NLS1 galaxies with flat X-ray spectra have lower $L_{\rm 1keV}/L_{\rm Edd}$.

orientation might play a secondary role in explaining AGN emission-line correlations and NLS1 properties in particular (e.g., Sulentic et al. 2000; Marziani et al. 2001; Boroson 2002; Bian & Zhao 2004b; Zhang & Wang 2006; Collin et al. 2006).

7. LOCUS ON THE M-SIGMA PLANE

Intimately linked to their high Eddington accretion rates and low black hole masses is the question whether NLS1 galaxies follow the $M_{\rm BH}-\sigma$ relation of BLS1 and normal galaxies (Mathur et al. 2001). NLS1 galaxies may hold important clues to the formation of this relation.

Employing different methods of measuring velocity dispersion σ (most often by using the width of [O III]λ5007 as substitute for stellar velocity dispersion), several authors found that NLS1 galaxies lie off the $M_{\rm BH}-\sigma$ relation (Mathur et al. 2001; Bian et al. 2004a; Grupe & Mathur 2004; Mathur & Grupe 2005a,b; Zhou et al. 2006), while other studies put them on the relation (Wang & Lu 2001; Botte et al. 2005). Different measurements of bulge luminosity L also place NLS1 galaxies on (Botte et al. 2004) or off (Wandel 2002; Ryan et al. 2007) the $M_{\rm BH}-L$ relation (see § 1 of Komossa & Xu 2007 for more detailed referencing). A main source of uncertainty, when examining the location of NLS1 galaxies on the $M_{\rm BH}-\sigma$ plane, regards the necessary corrections which need to be applied to both, measurements of [O III] width and of stellar absorption line width. [O III] line profiles are known to be complex and asymmetric. Stellar absorption lines could be affected by a systematic contribution of a disk component (and inclination effects) in non-ellipticals, gas absorption lines by outflows. The width of [O III] is most commonly used as surrogate for σ because the bulge velocity dispersion σ_* is very difficult to measure in NLS1 galaxies due to superposed emission-line complexes. Re-examining the usefulness of the width of [O III] as substitute for σ, and exploring the usefulness of [S II]λ6716,6731, Komossa & Xu (2007) found that NLS1 and BLS1 galaxies do follow the same $M_{\rm BH}-\sigma$ relation when using the width of [S II] to determine σ. Furthermore, the width of the *core* of the [O III] line is still a good surrogate for σ, but only after excluding objects which have their [O III] velocity field dominated by radial motions (presumably outflows) as manifested in significant blueshifts of these [O III] core lines (Figure 1).

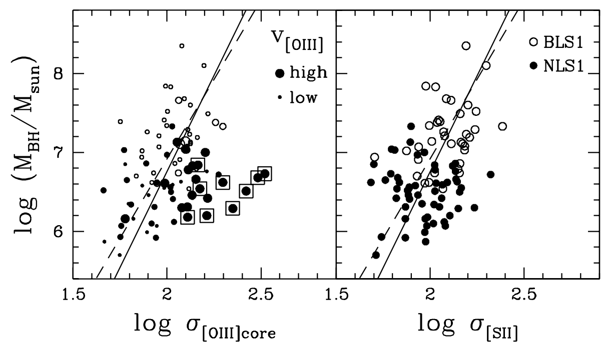

Fig. 1. Location of NLS1 galaxies (filled symbols) and BLS1 galaxies (open symbols) on the $M_{\rm BH}-\sigma$ plane (Komossa & Xu 2007). The **left panel** is based on σ measurements from the narrow core of [O III]λ5007 (asymmetric blue wings were removed). Circle size is coded according to the blueshift of the core of [O III]. 'Blue outliers' in [O III] (with radial velocities larger than 150 km s^{-1}) are marked with an extra open square. Once these blue outliers are removed, NLS1 and BLS1 galaxies follow the same $M_{\rm BH}-\sigma_{\rm [O\,III]}$ relation. The **right panel** shows the same relation based on [S II] (without any velocity coding; high outflow velocities only appear in [O III]). NLS1 and BLS1 galaxies follow the same $M_{\rm BH}-\sigma_{\rm [S\,II]}$ relation. The dashed and solid lines represent the $M_{\rm BH}-\sigma_*$ relation of non-active galaxies of Tremaine et al. (2002) and of Ferrarese & Ford (2005), respectively. σ is measured in km s^{-1}.

8. HOST GALAXIES

Relatively little is known about the host galaxies of NLS1 galaxies as a class. Krongold et al. (2001) studied host galaxies and environment of a sample of 27 NLS1s and concluded that they reside in similar environments as BLS1 galaxies, and tend to have smaller host galaxies. There are indications that the fraction of bars is higher in NLS1 galaxies than in BLS1s (Crenshaw et al. 2003; Ohta et al. 2007). Among galaxies with large-scale bars, NLS1 galaxies show a higher fraction of nuclear dust spirals and stellar nuclear rings which might indicate more efficient fueling of their black holes (Deo et al. 2006). NIR imaging of NLS1 host galaxies (selected to be of type E or S0) revealed that their bulges are redder than comparison samples of non-active and BLS1 galaxies (Ryan et al. 2007; see also Rodriguez-Ardila & Mazzalay 2006).

9. RADIO-LOUDNESS

Until recently, relatively little was known about the radio properties of NLS1 galaxies (Ulvestadt et al. 1995). Correlation analyses showed that radio loudness preferentially occurs in objects with broad Balmer lines and weak Fe II emission (e.g., Boroson & Greene 1992; Sulentic et al. 2003), leading to expectations that radio loudness in NLS1 galaxies might be rare. More studies of radio-loud NLS1 galaxies were needed to test this and to shed new light on our understanding of the NLS1 phenomenon, but also on radio loudness in general since a major unsolved question in the study of AGN concerns the key parameters that drive radio loudness (e.g., Wilson & Colbert 1995; Best et al. 2005; Capetti & Balmaverde 2006; Sikora et al. 2007). A systematic search for *radio-loud* NLS1 galaxies (Komossa et al. 2006) has shown that NLS1 galaxies as a class are not completely radio-quiet, but they are less likely to be radio loud than BLAGN. Only 7% of all NLS1 galaxies are radio loud (Komossa et al. 2006; Zhou et al. 2006), while only ∼2.5% of the NLS1s are 'very' radio loud (radio index $R > 100$)[6]. The radio-loud NLS1 galaxies are generally compact, steep spectrum sources in the radio regime and as such they share some similarities with the previously known class of compact steep-spectrum (CSS) radio sources. Estimates of black hole masses show that the radio-louds are at the upper range of NLS1 black hole masses, and are located in a previously scarcely populated area of $M_{\rm BH} - R$ diagrams. Optical properties of these radio-loud NLS1 galaxies are similar to the NLS1 population as a whole (Komossa et al. 2006; the same holds for a radio-selected NLS1 sample of Whalen et al. 2006). A surprising exception is that radio-loud NLS1 galaxies preferentially show moderate–strong Fe II emission when compared to radio-quiet NLS1s (Komossa et al. 2006). Mechanisms which drive the NLS1 radio properties (accretion rate, black hole spin, host galaxy properties and merger history) are still being explored.

There is recent evidence that several of the radio-loudest NLS1 galaxies display blazar characteristics and harbor relativistic jets (Zhou et al. 2007a; Doi et al. 2007; Yuan et al. 2007).

10. LINKS WITH OTHER TYPES OF SOURCES

BAL quasars. Similarities between broad absorption line (BAL) quasars and NLS1 galaxies, mostly based on their optical line properties, have been repeatedly pointed out (e.g., Brandt & Gallagher 2000; Boroson 2002; Grupe et al. 2007b, and references therein). Boroson (2002) finds that the two source populations, NLS1 galaxies and BAL quasars, are at similar ends of his EV1, but at opposite ends of EV2 (his Figure 7) which he interprets in terms of different accretion rates. A possible Rosetta stone to test such links is the NLS1 galaxy WPVS007, which showed a dramatic drop in its X-ray flux (Grupe et al. 1995, 2007a) that appears to be accompanied by the onset of BAL activity in the UV (Leighly et al. 2006).

Galactic black hole candidates. Pounds et al. (1995) pointed out the similarity of the X-ray spectrum of the NLS1 galaxy RE1034+39 to the high-state of Galactic black hole candidates, which led to more general speculations about links between these systems. Similarities in spectral and temporal properties between these two types of systems exist in the X-ray regime (e.g., Zycki 2001; Negoro 2004; McHardy et al. 2006) and perhaps with regard to their radio properties (Komossa et al. 2006), but further work is needed to explore how far these similarities go.

Evolutionary sequences. Links of NLS1 galaxies with other types of AGN have also been suggested in the context of evolutionary sequences. Mathur (2000) presented lines of evidence that NLS1 galaxies might be in an early stage of evolution. Kawakatu et al. (2007) discussed connections between NLS1 galaxies and ultraluminous infrared galaxies (ULIRGs; see also Hao et al. 2005) and proposed an evolutionary sequence from type 1 ULIRG to NLS1 to BLS1. Zhang & Wang (2006; see also Haas et al. 2007) suggest a link between NLS1 galaxies and non-HBLR Seyfert 2 galaxies (i.e., Sy 2 galaxies which lack a BLR even in polarized light), in the sense that NLS1 galaxies are the face-on equivalents of non-HBLR Sy2 galaxies, and Wang & Zhang (2007) discuss the temporal evolution of these systems into BLAGN.

11. SUMMARY

– It seems hard to resist the feeling that nature is telling us something important here, but we do not yet know what it is. Lawrence et al. (1997)

While our knowledge has increased significantly in the last decade, important questions are still open. For instance, what are sufficient, what are necessary conditions for the onset of NLS1 activity? For instance, the question is raised whether there are two types of Seyfert galaxies with low black hole masses: there is the unavoidable low-black-hole mass extension of BLS1 galaxies. Such systems would have their $\mathrm{FWHM}_{\mathrm{H}\beta}$ fall below the formal cutoff value of 2000 km s^{-1}. Does low black hole mass already imply the emergence of some or all of the typical observed NLS1 characteristics? Or is there a separate class of NLS1 galaxies? While many individual NLS1 galaxies have been studied in great detail,

[6]The fraction of radio-loud NLS1s in a purely radio-selected sample (Whalen et al. 2006) is higher, but even in that sample very radio loud objects are rare.

we still need larger samples free of selection biases and well-suited BLS1 comparison samples in order to identify robust trends. Correlation space will ultimately have to be expanded to include the radio and infrared properties of NLS1 galaxies, as well as the properties of their host galaxies. On the theoretical/modeling side, interesting questions that persist or have emerged are related to mechanisms of super-Eddington accretion, the simultaneous presence of (TeV) blazar activity and high accretion rate in extreme radio loud NLS1 galaxies, and mechanisms of fueling and feedback in NLS1 galaxies. The study of NLS1 galaxies will continue to provide important contributions to our understanding of AGN and their cosmic evolution.

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