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Narrow-line Seyfert 1 galaxies and the evolution of galaxies and active galaxies

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ABSTRACT

Narrow Line Seyfert 1 galaxies (NLS1s) are intriguing owing to their continuum as well as emission-line properties. The observed peculiar properties of the NLS1s are believed to be as a result of an accretion rate close to the Eddington limit. As a consequence of this, for a given luminosity, NLS1s have smaller black hole (BH) masses compared with normal Seyfert galaxies. Here we argue that NLS1s might be Seyfert galaxies in their early stage of evolution and as such may be low-redshift, low-luminosity analogues of high-redshift quasars. We propose that NLS1s may reside in rejuvenated, gas-rich galaxies. We also argue in favour of collisional ionization for production of Fe II in active galactic nuclei.

Key words: galaxies: active – galaxies: evolution – quasars: general – galaxies: Seyfert.

1 INTRODUCTION

Years after their discovery (Osterbrock & Pogge 1985) the NLS1s have attracted attention of the AGN community at least partly because of their peculiar X-ray properties. The NLS1s are Seyfert 1 galaxies with relatively narrow widths of permitted optical emission lines [full width at half maximum (FWHM) $\lesssim 2000\,\mathrm{km\,s^{-1}}$], strong optical Fe II/Hβ ratio, weak [O III] emission, and as such were found to occupy one extreme end of the Boroson & Green (1992) 'eigenvector 1'. An extremely strong anti-correlation was found between soft X-ray spectral slopes and Hβ FWHM in Seyfert 1s (Boller, Brandt & Fink 1996) and quasars (Laor et al. 1997) meaning that a relation between the lines and continuum exists. Eigenvector 1 was later found (Brandt & Boller 1998) to correlate strongly with the soft X-ray power-law slope. Since the soft X-rays are formed in the vicinity of the central black hole, eigenvector 1 has probably a more fundamental physical meaning.

NLS1s, as a class, show peculiar continuum properties as well. They have very steep soft X-ray slopes ($\langle\alpha\rangle = 2.13$, $F_\nu \propto \nu^{-\alpha}$, while for 'normal' Seyfert 1s $\langle\alpha\rangle = 1.34 \pm 0.03$) and sometimes show rapid large amplitude variability. The hard X-ray spectra are steep as well (Brandt, Mathur & Elvis 1997). In the optical and ultraviolet (UV) range, most of NLS1s show a weak 'big blue bump' (BBB), which is most likely owing to the shift of the BBB (sometimes out of the optical/UV range) towards higher energies. The high-energy tail of the BBB is apparent as the unusually strong and steep soft X-ray excess. NLS1s also show strong IR emission and some high polarization.

Many continuum properties of the NLS1s can be explained in terms of high accretion rate compared to the Eddington limit ($\dot{m} = \dot{M}/\dot{M}_{\mathrm{Edd}}$) and so, a small black hole (BH) mass for a given luminosity. The high accretion rate explanation for the X-ray properties of NLS1s was first proposed by Pounds, Done & Osborne (1995), in analogy with Galactic BH candidates whose soft X-ray spectra become steep in their high state. The narrow widths of the emission lines can be explained if the broad-line region (BLR) scales as $L^{1/2}$ and emission-line clouds are virialized around the small mass BH (Laor et al. 1997). As an alternative, Wandel (1997) has argued that the continuum, with steeper X-ray slope, has stronger ionizing power, and hence the BLR is formed at a larger distance from the centre. The resulting smaller velocity dispersion produces narrower lines. In general there is a reasonable consensus that large $\dot{m}$ is the cause of the observed peculiar properties of NLS1s (an alternative being a pole-on view). A natural question to ask as a next step would be 'what determines the accretion rate in an active galaxy?' Is it the age?

2 ARE NLS1s THE ACTIVE GALAXIES IN THE MAKING?

Here we present a number of arguments in support of our proposal that NLS1 might be active galaxies in early phase of their evolution.

(i) Smaller BH mass. As per the well known correlation of Magorrian et al. (1998) smaller mass BHs reside in galaxies with smaller spheroids. Since NLS1s have relatively smaller mass BHs compared to normal Seyferts, the spheroids of their host galaxies might be smaller (see also Laor, 1998). Indeed, in the compilation of Wandel (1999), the NLS1 galaxy NGC4051 has the smallest BH-to-bulge mass ratio. An accreting BH would also grow in mass with time [the Salpeter time-scale of growth is determined by $t_s = 3\times 10^7 (L_{\mathrm{Edd}}/L_B)\eta_{0.1}$ yr. where $\eta_{0.1}$ is the radiative efficiency in the units of 0.1 (see Fabian 1999)]. Since NLS1s accrete at close to Eddington limit, their BHs would grow faster. So, smaller BHs in NLS1s are likely to be younger as well.

(ii) Super-solar gas phase metallicities. There are a couple of lines of evidence to suggest that NLS1s may have super-solar gas phase metallicities. One comes from the study of high-ionization emission lines. Wills et al. (1999) found that the strength of N v λ1240 emission line was systematically larger while the strength of the C iv λ1549 was systematically smaller in AGN with narrow emission lines. The N v/C iv ratio serves as an abundance indicator as shown by Hamann & Ferland (1993). So, the NLS1s may have large nitrogen abundance. Absorption lines, being insensitive to density, serve as better indicators of metallicities. In the narrow-line AGN PG1404+226, Ulrich et al. (1999) found that while the strengths of Lyα and C iv absorption lines were in reasonable agreement with those expected from the ionized X-ray absorber (See Mathur 1997 for X/UV absorber models), the N v absorption line was significantly stronger. This observation, again, can be understood in terms of high nitrogen abundance in this narrow-line AGN (Mathur & Komossa, in preparation).

Large nitrogen abundance is obtained when overall metallicities are high with $N/H \propto (Z/Z_\odot)^2$ where $Z_\odot$ is the solar abundance. Nitrogen is preferentially enhanced because of secondary CNO nucleosynthesis (see Hamann & Ferland 1999, hereafter HF99, for details on AGN metallicities). Thus the observations of emission as well as absorption lines in NLS1s imply super-solar gas phase metallicities. The strength of the fluorescent Fe K alpha line in some NLS1s is also indicative of super-solar abundance (Fabian 1999).

Such metal enrichment is possible when the initial mass function of star formation is flat, favourable for high-mass star formation, and the evolution is fast. Such a star formation scenario is likely to be present in deep potential wells like galactic nuclei and protogalactic clumps (HF99). Moreover, high metallicities are achieved while consuming less gas (HF99). The NLS1s may then represent that early phase in galactic evolution when rapid star formation is taking place in the nucleus.

(iii) IR brightness. Many NLS1s are observed to be bright in the infrared (Moran, Halpern, & Helfand 1996). Young, star-forming galaxies are also bright IR sources. It is possible that a part of the nuclear IR flux is from a nuclear starburst.

(iv) Analogy with high-redshift quasars. In Section 3 we argue that NLS1s are analogous to very high-redshift quasars. High-redshift ($z > 4$) quasars are believed to quasars in the early phase of evolution compared to the $z \approx 1$ quasars. By analogy, NLS1s may as well be in the early evolutionary phase compared to the normal Seyfert galaxies.[1]

3 ARE NLS1s LOW-REDSHIFT ANALOGUES OF HIGH-REDSHIFT QUASARS?

That the AGN phenomenon was so much stronger at $z \sim 2$–3 than today has long elicited the suspicion that there is a connection between the youth of a galaxy and the likelihood that an AGN forms inside it. The question then naturally arises, 'what are the local counterparts to the young galaxies in early Universe, in which local AGN may live?' (see, e.g, Krolik 1999). A standard answer to this question is 'starburst galaxies'. Heckman (1999) has argued that starburst galaxies are the low-redshift analogues of Lyman break galaxies at high redshift. Similarly, we ask, what are the low-redshift analogues of high-redshift ($z \gtrsim 4$) quasars? We propose that they might be NLS1s.

It is interesting to note the similarity of the properties of NLS1s with high redshift ($z \gtrsim 4$) quasars.

(i) Hamann & Ferland (1993) found high metallicities in high-redshift quasars ($Z \gtrsim Z_\odot$ at $z \gtrsim 4$). Large metallicities in NLS1s may make them low-redshift, low-luminosity analogues of high-redshift quasars.

(ii) NLS1s and BALQSOs. Similarities between the observed properties of low-ionization broad absorption lines quasars (BALQSOs) and NLS1s have been reported in the literature (e.g. Lawrence et al. 1997; Leighly et al. 1997). Both these classes show strong Fe iiλ4570 and Al iiiλ1857 and weak C ivλ1549 and [O iii]λ5007 emission lines. Their continua are red in the optical and strong in the IR. Evidence of relativistic outflow is also reported in three NLS1s (Leighly et al. 1997). If these two classes are indeed related (Brandt 1999), then NLS1, at least those those with some evidence of outflow, might be low-redshift, low-luminosity cousins of BALQSOs. BALQSOs are tentatively identified with that phase in quasar evolution when the matter around the nuclear BH is being blown away, and a quasar emerges (see, e.g. Fabian 1999). NLS1s may then represent a similar early evolutionary phase at low redshift.

(iii) Optical spectra of a sample of $z \gtrsim 4$ quasars revealed that their emission lines are typically narrower than the low-redshift quasars (FWHM $\lesssim 2000\,\mathrm{km\,s^{-1}}$, Shields & Hamann 1997). The normal explanation of this observation is that these are type 2 quasars, where the broad emission lines are obscured from our line of sight. Alternatively, these high-z quasars might be true 'narrow' broad-line objects.

(iv) We note here another interesting connection with high redshift. As discussed in Section 1, NLS1s have strong Fe ii emission lines. Quasars Q0014+813 and Q0636+680 at redshifts $z = 3.398$ and $z = 3.195$ respectively, were observed to have very strong Fe ii emission (Elston, Thompson, & Hill 1994). Are they also highly accreting objects at early evolutionary phase? Note also the narrow UV emission lines (FWHM $\lesssim 2150\,\mathrm{km\,s^{-1}}$) in the ultra strong UV Fe ii emitter Q2226-3905 (Graham, Clowes & Campusano 1996).

All these similarities point towards NLS1s being low-redshift, low-luminosity analogues of high-redshift quasars.

4 DO NLS1s RESIDE IN REJUVENATED GALAXIES?

In the previous section we have argued that NLS1s may represent an early phase in AGN evolution. Whether they reside in young galaxies is a separate question and a step further. That young galaxies are gas rich is helpful; they would have the large reservoir of gas necessary to sustain the close to Eddington rate accretion in NLS1s. But do we have any evidence that they indeed reside in young galaxies? There is no published systematic study of the properties of the host galaxies of NLS1s. However, some of the NLS1s are originally from Zwicky (e.g. I Zw 1) and Markarian (e.g. Mrk 766) sample of galaxies implying that they are blue. While the blue colour might be owing to big blue bumps in the active nuclei, as in normal Seyfert galaxies, NLS1s have weak blue bumps (Section 1) and so the blue colours might be a result of

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[1] We note that Grupe (1996) has also argued that the age since an AGN was born might be the underlying reason for some NLS1-type correlations he has studied.

actively star-forming galaxies. Some NLS1s are *IRAS* galaxies (e.g. IRAS 13349+2438), infrared bright, and star forming. Using the catalogues of galaxies RC3 (de Vaucouleurs et al. 1991) and UGC (Nilson 1973) we looked into the morphology of a small sample of NLS1s with X-ray absorption features and found information on seven of them. Three were found to be compact (I Zw 1, Mrk 507, and Mrk 1298), two with signatures of inner ring (NGC 4051 and Ark 564), and three with nuclear bars (NGC 4051, Mrk 776 and Ark 564). These are signatures of recent activity, most likely due to galaxy–galaxy interactions or mergers. In this scenario the galaxies are newly formed, or rejuvenated.

That NLS1s reside in young galaxies is also consistent with the hypothesis that the formation and evolution of galaxies and their active nuclei is intimately related (Rees 1997; Fabian 1999; Granato et al. 2000; Haehnelt & Kauffmann 2000). In this scenario, the process of formation of a massive BH and the active nucleus is the very process of galaxy formation. The active nucleus and the galaxy evolve together, with BH accreting matter and the galaxy making stars. At one stage the winds from the active nucleus blow away the matter surrounding it and a quasar emerges. This is not only the end of active evolution of the quasar but that of the galaxy as well, which is evacuated of its interstellar medium. The quasar then shines as long as there is fuel in the accretion disc (Fabian 1999). In this scenario, high-redshift quasars represent early stage of galaxy evolution, BALQSOs at $z \approx 2$ represent the stage when the gas is being blown away and $z \approx 1$ quasars would be the passively evolving population. Massive ellipticals found today might be the dead remnants of what were once quasars.

The quasar phenomenon may thus be a result of galaxy formation owing to primordial density fluctuations. At low redshift, when new galaxies are formed as a result of interactions or mergers, similar evolution may take place. As argued above, the NLS1s may represent a crucial early phase. [In our scenario, the accretion rate $\dot{m}$ is large in the early stages of evolution and reduces later on. This is opposite to the proposal by Wandel (1999) in which $\dot{m}$ increases with time.]

In fact, there might be some NLS1s with a starburst component (see Section 2). Soft X-ray spectra of NLS1 are steep and often variable. However, Leighly et al. (1996) and Page et al. (1999) report that while the power-law component in the NLS1 Mrk 766 varied, the thermal black-body component did not. This component might well be owing to a nuclear starburst. Note also the strong CO emission in the prototype NLS1 I Zw 1 (Barvainis, Alloin & Antonucci 1989). Schinnerer, Eckart & Tacconi (1998) mapped I Zw 1 in Co and found a circumnuclear ring of diameter 1.8 kpc. The authors found strong evidence for a nuclear starburst. There is also a companion to I Zw 1, supporting an interpretation of starburst due to interaction. Similarly, AGN activity is known to exist in starburst galaxies (see Heckman 1999 for a review). Dennefeld et al. (1999) report observations of narrow optical emission lines in a sample of IR selected starburst galaxies.

5 OBSERVATIONAL TESTS

Here we propose several observations that could test the ideas presented above. (1) Emission-line properties of high redshift quasars: objects in the Shields & Hamann sample, for example, were selected on the basis of their colours, in particular very red $B - R$ which results when Lyα is redshifted into the R band. This could lead to a selection bias in favour of objects with narrow, peaky profiles (Shields & Hamann 1997). It would be important to remove such selection bias before we can conclude that $z > 4$ quasars have narrow emission lines. A broader wavelength coverage with more than just two bands would be useful. The 'drop-out' technique (Steidel, Pettini & Hamilton 1995) used for finding Lyman break galaxies would be another way to remove emission line bias. (2) X-ray properties of high-redshift quasars: only about a dozen $z > 4$ quasars are detected in X-rays (see the latest update by Kaspi, Brandt & Schneider 2000). However, X-ray spectra of $z > 4$ quasars are still not available. It will be interesting to see if they are steep, and highly variable like those of NLS1s. We will be studying X-ray spectra of radio-loud as well as radio quiet $z > 4$ quasars with *XMM*. (3) Morphology and environment of NLS1s: are NLS1s preferentially found in younger galaxies and/or in more disturbed environments? A systematic study of host galaxy properties of a well-defined sample of NLS1s is needed. (4) Search for starburst components in NLS1s: evidence for the starburst–NLS1 connection (Section 4) is suggestive, but not yet statistically sound. Do the nuclear components of starburst galaxies show narrow emission lines? Do NLS1s show evidence of a starburst component more often than normal Seyferts? Spectroscopic as well as high-resolution imaging observations would help towards establishing the connection between the two.

6 ON THE CORRELATION OF FE II STRENGTH AND X-RAY SPECTRAL SLOPE

While photoionization models reproduce the properties of optical and UV emission lines observed in AGN spectra with reasonable success, the case of Fe II lines is different. Wills, Netzer & Wills (1985) found that standard photoionization models cannot explain the strength of the the observed Fe II lines in AGN. Collin-Souffrin and collaborators (Collin-Souffrin, Hameury & Joly 1988) as well as Kwan (1984) advocated that collisional ionization would be important in the production of Fe II. Collin (1999) has again shown that strong Fe II emission cannot be produced by photoionization with any set of parameters, and even by making iron abundance reasonably super-solar. The importance and necessity of collisional ionization of iron was, however, not appreciated at least in part due to the observed correlation between Fe IIλ4570 equivalent width and the soft X-ray energy index (Wilkes, Elvis & McHardy 1987; Shastri et al. 1993). Standard photoionization models for the line emission from the broad-line regions of quasars (Krolik 1988) imply a close link between the energy index of the ionizing X-ray continuum and the strength of emission lines. So the Wilkes et al. and Shastri et al. correlation was interpreted as a result of photoionization. Note, however, that the correlation is in in the opposite sense to that predicted by the standard photoionization model in which Fe II emission is generated deep within the cloud and thus is sensitive to harder X-rays. NLS1s may provide us with the clue to understand this observed, conflicting trend as discussed below.

As discussed in Section 1, there is a general consensus that large accretion rate, $\dot{M}/\dot{M}_{\rm Edd}$, is the likely driver of the many observed properties of NLS1s. Large strength of Fe II emission may then be linked to the large accretion rate. In a model by Kwan et al. (1995) Fe II line emission is produced in an accretion disc. The accretion discs with larger accretion rate may simply have more mass to produce stronger Fe II. Thus we argue that the observed correlation of Fe II strength and soft X-ray slope is a consequence of the correlation with the accretion rate and support collisional ionization as the origin.

7 CONCLUSIONS

We have argued that NLS1s are likely to be AGN in the making and reside in rejuvenated galaxies. As such they represent a crucial early phase in the evolution of galaxies and active galaxies. What we need now is a systematic study of host galaxy properties of a well-defined sample of NLS1s and their comparison with the hosts of normal Seyferts. Some evidence presented above is based on a small number of objects and generalization may not be appropriate. Studies at high redshift also suffer from selection effects. Understanding and correcting for them is crucial in establishing the analogy with NLS1s on a firm footing. X-ray spectra of high-redshift radio-quiet quasars will provide an addition piece of information towards this goal. It would of great interest to find out whether starburst galaxies are the parent population of NLS1s.

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