A COMPREHENSIVE STUDY OF 2000 NARROW LINE SEYFERT 1 GALAXIES FROM THE SLOAN DIGITAL SKY SURVEY. I. THE SAMPLE

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ABSTRACT

This is the first paper in a series dedicated to the study of the emission-line and continuum properties of narrow line Seyfert 1 galaxies (NLS1s). We carried out a systematic search for NLS1s from objects assigned as “QSOs” or “galaxies” in the spectroscopic sample of the Sloan Digital Sky Survey Data Release 3 (SDSS DR3) by a careful modeling of their emission lines and continua. The result is a uniform sample comprising ~2000 NLS1s. This sample dramatically increases the number of known NLS1s by a factor of ~10 over previous compilations. This paper presents the parameters of the prominent emission lines and continua, which were measured accurately with typical uncertainties <10%. Taking advantage of such an unprecedented large and uniform sample with accurately measured spectral parameters, we carried out various statistical analyses, some of which were only possible for the first time. The main results found are as follows. (1) Within the overall Seyfert 1 population, the incidence of NLS1s is strongly dependent on the optical, X-ray, and radio luminosities as well as the radio loudness. The fraction of NLS1s peaks around SDSS g-band absolute magnitude Mg ~ -22 mag in the optical and ~10^{-4.2} ergs s^{-1} in the soft X-ray band, and decreases quickly as the radio loudness increases. (2) On average the relative Fe ii emission Fe ii \lambda \lambda 4434, 4684/H\beta in NLS1s is about twice that in normal active galactic nuclei (AGNs) and is anticorrelated with the broad component width of the Balmer emission lines. (3) The well-known anticorrelation between the width of broad low-ionization lines and the soft X-ray spectral slope for broad line AGNs extends down to FWHM ~ 1000 km s^{-1} in NLS1s, but the trend appears to reverse at still smaller line widths. (4) The equivalent width of H\beta and Fe ii emission lines are strongly correlated with the H\beta and continuum luminosities. (5) We do not find any difference between NLS1s and normal AGNs in regard to the narrow line region. (6) We have examined the black hole mass versus stellar velocity dispersion (M_{BH} - \sigma) relation for a subsample of 308 NLS1s for which \sigma could be measured directly from fitting the starlight in the SDSS spectra with our stellar spectral templates. A significant correlation between M_{BH} and \sigma is found, but with the bulk of black hole masses falling below the values expected from the M_{BH} - \sigma relation for normal galaxies and normal AGNs. This result indicates that NLS1s are underage AGNs, where the growth of the SMBH lags behind the formation of the galactic bulge. (7) We also find that the FWHM of [N ii] line is well correlated with \sigma, in 206 NLS1s, for which both parameters could be derived with reasonable accuracy. The [N ii] width can predict the stellar velocity dispersion to an accuracy of ~30%. A similar M_{BH} - \sigma relation could be found for a larger sample of 613 NLS1s on making use of the more reliable measurements of FWHM[N ii].

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1. INTRODUCTION

Active galactic nuclei (AGNs)—Seyfert galaxies and quasars—are characterized by nonthermal continuum emission over almost the whole electromagnetic spectrum from their nuclei and prominent emission lines in the ultraviolet and the optical. The overall spectral energy distribution (SED) can be described as an underlying power law of the form F_{\nu} \propto \nu^{-s} interspersed with bumps and dips. The AGNs can be classified into two types according to their emission spectrum: type 1 AGNs show both broad emission lines with full width at half-maximum (FWHM) of a few thousand km s^{-1} and narrow emission lines of a few hundred km s^{-1}, while type 2 AGNs show only narrow emission lines. Permitted and semiforbidden lines are seen with both broad and narrow profiles, while forbidden lines are seen only with narrow profiles. It was recognized at the end of the 1970s (e.g., Osterbrock 1978) that such a split might be an orientation effect involving obscuration of the broad-line region (BLR). According to unification models, all AGNs have intrinsically the same physical structure, but in type 2 AGNs the BLR and continuum emission region are obscured by a presumed dusty torus located somewhere between the BLR and the narrow line region (NLR).

It seems that the division of AGNs into type 1 and type 2 is well defined and the evidence for unification schemes is compelling (cf. Antonucci 1993). Interestingly, almost at the same time when the unified models were first brought forward, it was found that two objects, Mrk 359 (Davidson & Kinman 1978) and Mrk 42 (Koski 1978; Phillips 1978), have all the spectral properties of a typical type 1 AGN, except that the “broad permitted lines” are comparable in width to the forbidden lines as in the case of type 2 AGNs. Some other unusually narrow “broad line emitters” (e.g., Mrk 493 and Mrk 783; Osterbrock & Dahari 1983) were identified in the following years. This intriguing mixture of features makes this “peculiar” group of AGNs very interesting. Osterbrock & Pogge (1985, hereafter OP85) denoted these objects as narrow line Seyfert 1 galaxies (NLS1s). Their original classification included the following two empirical and somewhat subjective criteria: (1) the Balmer lines are only slightly broader than forbidden lines; and (2) the line ratio [O iii] \lambda 5007/H\beta < 3; but
exceptions are allowed when strong high-ionization iron lines, such as [Fe vi] $\lambda$6087 and [Fe x] $\lambda$6375 are present, which are seldom seen in type 2 AGNs. In his spectropolarimetric study of NLS1s, Goodrich (1989) treated them as an extension of normal broad-line Seyfert 1 galaxies (hereafter BLS1s) to lower FWHM of permitted lines and quantified the first criterion of OP85 with FWHM(H$\beta$) < 2000 km s$^{-1}$.

Apart from the unusually narrow Balmer lines, NLS1s often show the strong permitted Fe II emission lines in their optical and ultraviolet spectra; they also show some other extreme properties, such as a steep soft X-ray spectrum, rapid X-ray variability, dense line-emitting gas, and a commonly blue shifted UV line profile (Boller et al. 1996; Leighly 1999; Aoki & Yoshida 1999; Wills et al. 1999; Leighly 2000). In fact, these properties are extensions of the following correlations between various observables and the H$\beta$ line width (Boroson & Green 1992; Laor et al. 1994; Wang et al. 1996): the narrower the H$\beta$ line, the steeper the X-ray spectrum, the stronger the H$\beta$ blue wings, the faster the X-ray variation, the stronger the optical Fe II emission, the weaker the [O iii] lines, and the denser the BLR clouds. These form the so-called eigenvector 1 (E1; Boroson & Green 1992; Sulentic et al. 2000). E1 is taken as the strongest and most far-reaching type 1 AGN unification yet discovered (e.g., Marziani et al. 2001), which incorporates the geometry, kinematics, and physical condition of the central regions in AGNs. Its underlying physical driver is related to either the basic physical parameters of the black hole accretion disk such as the black hole mass and accretion rate, or geometrical parameters such as the viewing angle (Boroson & Green 1992; Boller et al. 1996; Wang et al. 1996; Laor et al. 1997; Sulentic et al. 2000; Marziani et al. 2001; Xu et al. 2003). Since NLS1s lie at the extreme negative end of E1, they may well occupy some extreme regions in the parameter space of some primary physical parameters, whatever they are. We can, therefore, use the unusualness of NLS1s to test the viability of the different AGN models.

However, some of the basic properties of NLS1s remain unclear even though it has been two decades since their first identification. We summarize these issues under the following two headings.

Properties extensively explored, but no consensus reached yet.—(1) For Seyfert 1 galaxies and QSOs, a correlation between the soft X-ray photon index (from ROSAT observations) and the H$\beta$ line FWHM has now been well established (Laor et al. 1994; Boller et al. 1996; Wang et al. 1996). In comparison, for the NLS1s, which have on average steeper photon indices, the same correlation shows a larger dispersion. It is still not known whether the flatness of the X-ray spectra of some NLS1s is intrinsic or due to internal absorption. (2) Boroson & Green (1992), McIntosh et al. (1999) and Grupe et al. (1999) found that the strength of the Fe ii and [O iii] lines are anticorrelated, but this was not confirmed by Véron-Cetty et al. (2001, hereafter VVG01). It is unclear whether this correlation should be included in E1. (3) Rodríguez-Ardila et al. (2000) claimed that the emission line ratio of the narrow line region (NLR), [O iii]/H$\beta$, is in the range of $\sim$1–5 for NLS1s, significantly less than the values $\sim$10, typical of normal AGNs, while VVG01 did not find any difference between the two types.

Virgin territories.—Compared to the well-studied emission line and X-ray properties of NLS1s, little or no attention has been given to (1) their broadband continuum properties; (2) the relationship between the NLS1 phenomena and the evolution of the host galaxies; (3) the type 2 counterparts of NLS1s predicted by AGN unification models; and (4) their spectral variability.

To resolve the controversies and to seek new insights, it would be helpful to have a large-size homogeneous sample of optically selected NLS1s with accurately measured parameters of both narrow and broad lines. The Sloan Digital Sky Survey (SDSS; York et al. 2000) is expected to be able to provide such NLS1 samples resulting from well-defined selection criteria that are large enough for serious statistical studies; furthermore, it is expected that potentially peculiar and interesting objects will be identified and studied with follow-up observations. The first attempt in this direction was made by Williams et al. (2002, hereafter WPM02), who compiled a sample of NLS1s from the SDSS Early Data Release (EDR; Stoughton et al. 2002), which comprised 150 objects. With a roughly tenfold increase in size over the EDR, the currently available SDSS spectroscopic data can be expected to yield many more NLS1s for the study.

We carried out a systematic search for NLS1s from the spectroscopic sample of the Sloan Digital Sky Survey Data Release 3 (SDSS DR3; Abazajian et al. 2005). In order to obtain from SDSS spectra accurate and reliable line widths that are essential for the selection and the follow-on analyses, we carefully fitted emission lines, AGN continuum, and starlight in a self-consistent manner. As a result, we now have a uniform sample comprising as many as 2011 NLS1s. The accurately measured emission-line parameters and hence the selection of sample objects are an improvement on WPM02, rendering our sample less affected by selection biases compared to WPM02. This paper is the first of a series that reports on our ongoing project for extensive studies of NLS1s by fully exploring the potential of this large-size sample. Here we present the object catalog, which will be kept updated as new SDSS data are further available; also presented are some preliminary statistical results on the sample as a whole. We shall attempt to address some of the issues raised above in forthcoming papers. The plan of this paper is as follows: In the next section, we describe in detail the methods we used to process all the low-redshift QSOs and galaxies in the SDSS DR3. The sample selection is described in § 3. The properties of the sample are discussed in § 4, including a statistical analysis of the emission lines and remarks on potentially interesting individuals. We explore the black hole–bulge relation for NLS1s in § 5. Our main results are summarized in the last section, followed by prospects of future work.

2. OPTICAL SPECTRAL ANALYSIS

2.1. An Overview

Our NLS1s were selected from the SDSS DR3 catalogs that are classified as “galaxy” or “QSO” by the SDSS spectroscopic pipeline. Only objects with a redshift $z \leq 0.8$ were considered to ensure that the H$\beta$ and [O iii] emission lines would fall within the wavelength coverage of the SDSS spectrograph (details of SDSS spectroscopy can be found in Stoughton et al. 2002). The spectra of the resulting 387,483 extragalactic objects (12,824 “QSOs” and 374,659 “galaxies”) were first corrected for the Galactic extinction using the extinction curve of Schlegel et al. (1998) and then shifted back to their rest frames using the redshifts provided by the SDSS pipeline.

Contamination from stellar light.—The fibers that feed the SDSS spectrograph subtend a diameter of 3′′ on the sky, which corresponds to $\sim$6.5 kpc at $z = 0.1$. AGN spectra taken through such a fixed aperture may include significant light from the host galaxies, as exhibited in the composite spectra of SDSS quasars (Vanden Berk et al. 2001). Careful removal of the starlight is essential for reliable measurement of the emission lines, and hence
correct identifications of NLS1s from the huge SDSS data. Actually, the starlight “contamination” provides valuable information about the host galaxies, which is of interest in itself. For this and other purposes, we have developed a technique of properly modeling the stellar component (see Lu et al. 2006 for details of the method). This method decomposes the SDSS spectra of active galaxies into stellar and nonstellar nuclear components, provided that the two components are comparable in strength. A description of this method is given in § 2.2.

Broad-line and narrow-line decomposition.—The Balmer emission lines of NLS1s may include significant contribution from narrow-line components (VVG01; Rodriguez-Ardila et al. 2000). In the selection of NLS1s based on the line’s FWHM, it is therefore more appropriate to use the broad component rather than the total emission line, as was done in WPM02. Moreover, the deblended narrow components have interest of their own for the study of the NLR properties in NLS1s. We therefore performed emission-line decomposition in the analysis. For reliable line decomposition, good spectral quality is required in terms of both S/N ratio and spectral resolution. Rodriguez-Ardila et al. (2000) demonstrated that spectra with a high S/N ratio (the exact value is unclear but likely to be around 30 per pixel) and a moderate resolution (340 km s$^{-1}$ FWHM at H$\alpha$) are sufficient for the decomposition of the permitted emission lines in NLS1s. In comparison, the SDSS spectra used in this work have a somewhat lower S/N on average but better resolution (estimated to be 132 ± 12 km s$^{-1}$ FWHM at H$\alpha$; cf. Greene & Ho 2005); the effect of the latter compensates the effect of the former. Spectral decomposition was also carried out in VVG01, in which the spectral resolution (FWHM ∼ 3.4 Å) was actually a little bit worse than that of the SDSS spectra. We therefore anticipate that the spectral quality of the SDSS data is adequate for our purposes, at least for the majority of objects. A detailed account of spectral-line fitting is presented in § 2.3.

Spectral fitting procedure.—In the processing of this large data set we employed a two-step iteration procedure, which is outlined below and detailed in the following two subsections. The continua of the broad emission-line AGN candidates were first decomposed into starlight and nuclear components. Beforehand, two kinds of spectral regions had been masked out: first, bad pixels as flagged by the SDSS pipeline; second, the wavelength ranges that may be seriously affected by prominent emission lines characteristic of QSO spectra. To determine the latter, the composite SDSS QSO spectrum (Vanden Berk et al. 2001) was used during the first iteration. A pseudocontinuum was fitted and subtracted, which was chosen as a non-negative linear combination of properly generated templates taking into account the contribution from both starlight and nucleus (§ 2.2). The left-over emission-line spectrum was fitted with Gaussian and/or Lorentzian profiles, separating broad and narrow line components (§ 2.3). Then the measured emission line spectrum was used to replace the composite SDSS spectrum in the second iteration. This procedure was reiterated until the fitted parameters of both the continuum and the emission-line spectrum converged to an acceptable accuracy.

2.2. Decomposing Starlight and Nuclear Continuum

We modeled the pseudocontinuum of the 387,483 SDSS galaxies and QSOs with two to four components

$$S(\lambda) = A_{\text{host}}(E_{B-V}^{\text{host}}, \lambda)A(\lambda) + A_{\text{nucleus}}(E_{B-V}^{\text{nucleus}}, \lambda)[bB(\lambda) + cC(\lambda) + dD(\lambda)],$$

where $S(\lambda)$ is the observed spectrum. $A(\lambda) = \sum_{i=1}^{6} a_i IC(\lambda, \sigma_i)$ represents the starlight component modeled by our six synthesized galaxy templates, which had been built up from the spectral template library of simple stellar populations (SSPs) of Bruzual & Charlot (2003, hereafter BC03) using our new method based on the Ensemble Learning Independent Component Analysis (EL-ICA$^4$) algorithm. The merits of these galaxy templates are that, first, their physical meanings are clear; second, in most cases, an overfit to the spectra can be avoided because the most prominent features of the BC03 SSP library are embodied to the greatest extent in only six non-negative independent components (ICs). The details of the galaxy templates and their applications are presented in Lu et al. (2006). $A(\lambda)$ was broadened by convolving with a Gaussian of width $\sigma$, to match the stellar velocity dispersion of the host galaxy. The unresolved nuclear continuum is assumed to be $B(\lambda) = \lambda^{-1.7}$ as given in Francis (1996). $C(\lambda)$ denotes the optical Fe II templates of Véron-Cetty et al. (2004) with the width fixed to that of the broad component of H$\beta$. $D(\lambda)$ represents the templates of higher order Balmer emission lines (10 ≤ n ≤ 50) and Balmer continuum generated in the same way as in Dietrich et al. (2003). $A_{\text{host}}(E_{B-V}^{\text{host}}, \lambda)$ and $A_{\text{nucleus}}(E_{B-V}^{\text{nucleus}}, \lambda)$ are the color excesses due to the extinction of the host galaxy and the dusty torus, respectively, assuming the extinction curve for the Small Magellanic Cloud (SMC) of Pei (1992). The fitting was performed by minimizing the $\chi^2$ with $E_{B-V}^{\text{host}}, E_{B-V}^{\text{nucleus}}, a_i, \sigma, b, c,$ and $d$ being non-negative free parameters.

To reduce the amount of computation, $E_{B-V}^{\text{host}}, E_{B-V}^{\text{nucleus}}, c,$ and $d$ were fixed at zero during the first iteration. Then the modeled continuum was subtracted from the observed spectrum and the emission line parameters were measured in the way described in § 2.3. The variables $E_{B-V}^{\text{host}}$ and $E_{B-V}^{\text{nucleus}}$ were set to be free parameters when the continuum was fitted the second time. For those objects in which the H$\beta$ broad emission line is reliably detected (at the $\sim 5 \sigma$ confidence level), $c$ and $d$ were also set free, and the width of the Fe II multiplets was fixed to that of the H$\beta$ broad component. This time the wavelength ranges of the emission lines to be masked out were determined using the measured line parameters. The iteration continued until the fitted parameters of both the modeled stellar spectrum and the emission-line spectrum converged to an acceptable accuracy. Representative examples of the EL-ICA starlight–nuclear decomposition are shown in Figure 1.

2.3. Emission-Line Fitting

The emission-line fitting procedure adopted here is similar to that used in Dong et al. (2005), but with some modifications in the codes to improve the accuracy of the measurement of the broad components of H$\beta$ and H$\alpha$, as described in the following. The emission lines are decomposed into a broad and a narrow component whatever the latter contributes non-negligibly. The [N ii] doublet are separated from H$\alpha$.

All narrow emission lines, except the [O iii] doublet, were fitted with a single Gaussian because these lines are often quite weak in NLS1s and the S/N is not high for most objects. The [O iii] doublet were fitted either with a single Gaussian if the profile is symmetrical or of low S/N, or with a double Gaussian $^4$ ICA is a new Blind Source Separation (BSS) method for finding underlying statistically independent, non-Gaussian components from multidimensional data. This statistical and computational technique can be regarded as an extension to Principle Component Analysis (PCA) but is much more powerful than the latter. The Ensemble Learning algorithm is an approach to find an analytic approximation applicable to the ICA model (Miskin & MacKay 2001).
otherwise. The flux ratios of the [O iii] and [N ii] doublets were fixed at their theoretical values. The profile and redshift of the Hα narrow component were assumed to be the same as those of the [N ii] and [S ii] doublets;—this approach is often adopted in separating the narrow and broad components in the Hα + [N ii] + [S ii] regime (e.g., Ho et al. 1997; VVG01; Dong et al. 2005). This assumption can be tested using type 2 AGNs, where narrow emission lines can be measured much more easily. Here we carried out such a test using a sample of ~3000 type 2 AGNs with high S/N spectra from SDSS. Figure 2 shows FWHM[N ii] (upper left

Fig. 1.—Representative examples of the EL-ICA starlight-nucleus decomposition. In each panel, we plot the observed spectrum (black), the combination of the models (red), the decomposed components of the host galaxy (blue), the power-law continuum of the nucleus (green), and the Fe ii multiplets (pink). The observed spectra are smoothed with a boxcar of 5 pixels for the illustration.
It can be seen that both FWHM[N II] and FWHM[S II] are statistically well consistent with FWHM(H/Hα). For this type 2 AGN sample, then, we made a second fit after tying together the profiles and redshifts of H/Hα, [N II], and [S II] 6548, 6583, and [S II] 6716, 6731.

The fitted line width was compared with that of H/Hα, and a good agreement was found (Fig. 2, lower left panel). FWHM(H/Hα) was also found to be well correlated with FWHM([O III]), although the scatter is much larger than in the FWHM(H/Hα)–FWHM[N II] correlation. We therefore consider it a good approximation to tie the profile and redshift of the narrow component of H/Hα—in the case of weak lines, either narrow or broad—to the fitted values of H/Hα + [N II] or [O III]. We refer to these schemes as “H/Hα to H/Hα” and “[O III] to H/Hα,” respectively.

In the first place, each of the forbidden and permitted lines was fitted with a single Gaussian. Objects were assigned as candidates of broad emission-line AGNs if their Balmer emission line(s) were significantly broader than the forbidden lines or their Fe II multiplets were detected at the ≥5σ confidence level. The spectra of more than 6000 candidates from the SDSS “galaxy” catalog were visually inspected, and 12,824 objects with z < 0.8 in the SDSS “QSO” catalog, were carried over into the second iteration stage. After the continuum was subtracted, the H/Hα and H/β emission lines were fitted with two Gaussians, one for the narrow and one for the broad component. As mentioned above, the width and redshift of the narrow component of H/Hα were tied to those of the [N II] and [S II] doublets; and for the narrow component of H/β, the “H/Hα to H/β” (for z < 0.39) or “[O III] to H/β” (for 0.39 < z < 0.8) schemes were adopted. The objects were reserved whose broad component(s) of H/Hα or H/Hα were detected at the >10σ level with the FWHM less than 3000 km s⁻¹. All the rejected objects were double-checked for confirmation by visual inspection to ensure that no true NLS1s were missed (actually such checks were made throughout the whole selection process whenever an object was to be rejected). We also rejected at this stage the narrow emission line galaxies that were misclassified as “QSOs” by the SDSS pipeline. At the stage of the third iteration, the broad components of H/Hα and H/β were fitted with a Lorentzian profile, while the narrow lines were fitted in the same way as in the second iteration. Only those having FWHM(H/Hα) or FWHM(H/β) less than 2500 km s⁻¹ were carried over into the last iteration stage. The emission lines were then fitted using one of the following four schemes in order of decreasing preference: (1) the broad and narrow components of H/β are deblended freely; (2) the “H/Hα to H/β” scheme; (3) the “[O III] to H/β” scheme; and (4) H/Hα.

![Fig. 2.— Comparison of the narrow emission-line widths for ~3000 high S/N type 2 AGNs. In the upper two panels, H/β, [N II] and [S II] lines are all fitted with a single Gaussian. The profiles and redshifts of the [N II] doublet are tied, and so are the [S II] doublet. The flux ratio of the [N II] doublet is fixed to its theoretical value. It can be seen that FWHM(H/β) agrees well with FWHM[N II] and FWHM[S II]. In the lower left panel, FWHM[N II] is compared to FWHM(H/β). The profiles and redshifts of the [N II] doublet are tied to that of H/β and [S II] during the measurement of these lines. It can be seen that FWHM[H/β] agrees with FWHM[N II] within their respective uncertainties. FWHM(H/β) is plotted against FWHM([O III]) in the lower right panel. The scatter is much larger than those in the other three relations.

panel) and FWHM[S II] (upper right panel) against FWHM(H/Hα). It can be seen that both FWHM[N II] and FWHM[S II] are statistically well consistent with FWHM(H/Hα). For this type 2 AGN sample, then, we made a second fit after tying together the profiles and redshifts of H/Hα, [N II] 6548, 6583, and [S II] 6716, 6731. The fitted line width was compared with that of H/β, and a good agreement was found (Fig. 2, lower left panel). FWHM(H/β) was also found to be well correlated with FWHM([O III]), although the scatter is much larger than in the FWHM(H/β)–FWHM[N II] correlation. We therefore consider it a good approximation to tie the profile and redshift of the narrow component of H/β—in the case of weak lines, either narrow or broad—to the fitted values of H/Hα + [N II] or [O III]. We refer to these schemes as “H/Hα to H/β” and “[O III] to H/β,” respectively.
and Hβ lines are fitted with a single Lorentzian (for objects having no isolated narrow emission line detected or having too noisy spectra). The fitting results were visually inspected before acceptance. Only 42 objects could not be fitted satisfactorily by using the above procedure. Among those exceptions, the majority have the broad components of Hβ or Hα too narrow to separate from the narrow components; the remaining have their redshifts incorrectly assigned by the SDSS pipeline. Their spectra were fitted manually.

Figure 3 shows a few examples of emission-line decomposition in the Hα and Hβ wavelength ranges.

3. SAMPLE SELECTION

3.1. Selection Criteria

Based on the emission line parameters measured, we compiled our NLS1 sample. The only criterion we adopted for identifying
# Emission-Line Properties of SDSS NLS1s

| Object (1) | Redshift (2) | $\lambda L_{\lambda}5100^a$ (3) | FC$^b$ (4) | $F(H\beta)^c$ (5) | $F(H\beta)^d$ (6) | FWHM($H\beta^c$) (7) | $F[O\,iii]^c$ (8) | $F(H\alpha)^c$ (9) | FWHM($H\alpha$) (10) | $F[N\,ii]^c$ (11) | FW$^{[N\,ii]}^d$ (12) | $R_{4570}$ (13) |
|------------|--------------|-------------------------------|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------------|
| 000011.41+145545.7 ...... | 0.459621 | 44.28 | 0.65 | 2 ± 1 | 257 ± 7 | 1088 ± 40 | 46 ± 3 | 0.64 ± 0.06 |
| 000109.13—004121.7 ...... | 0.416622 | 44.33 | 0.66 | 28 ± 6 | 287 ± 11 | 1629 ± 135 | 91 ± 2 | 0.69 ± 0.07 |
| 000154.27+000732.5 ...... | 0.139595 | 43.31 | 0.30 | 97 ± 4 | 420 ± 16 | 1872 ± 106 | 655 ± 6 | 386 ± 7 | 1269 ± 15 | 1614 ± 31 | 142 ± 3 | 183 ± 4 | 0.22 ± 0.05 |
| 000208.83—001742.7 ...... | 0.651891 | 44.69 | 0.82 | 296 ± 13 | 1470 ± 77 | 60 ± 4 | 1.36 ± 0.12 |
| 000257.37—000015.0 ...... | 0.516586 | 44.42 | 0.70 | 230 ± 8 | 959 ± 44 | 64 ± 6 | 1.06 ± 0.09 |
| 000410.81—104527.1 ...... | 0.239706 | 44.28 | 0.77 | 65 ± 6 | 697 ± 14 | 1137 ± 39 | 86 ± 6 | 218 ± 13 | 2204 ± 24 | 1035 ± 20 | 147 ± 5 | 199 ± 8 | 1.49 ± 0.07 |
| 000834.72+003156.2 ...... | 0.263034 | 44.45 | 0.78 | 56 ± 10 | 1381 ± 21 | 1537 ± 44 | 94 ± 5 | 160 ± 24 | 3467 ± 38 | 1302 ± 25 | 41 ± 7 | 289 ± 31 | 1.28 ± 0.04 |
| 000913.79—102124.7 ...... | 0.614361 | 44.64 | 0.68 | 1 ± 3 | 257 ± 14 | 1380 ± 110 | 53 ± 5 | 1.18 ± 0.17 |
| 001010.03+005126.6 ...... | 0.387000 | 44.17 | 0.57 | 5 ± 2 | 143 ± 10 | 2014 ± 183 | 43 ± 3 | 30 ± 6 | 400 ± 26 | 1779 ± 164 | 8 ± 3 | 163 ± 43 | 1.15 ± 0.18 |
| 001100.32+134812.2 ...... | 0.686029 | 44.78 | 0.88 | 2 ± 1 | 384 ± 13 | 1468 ± 68 | 15 ± 3 | 0.99 ± 0.10 |
| 001104.85—092357.9 ...... | 0.695986 | 44.88 | 0.80 | 394 ± 14 | 1401 ± 64 | 26 ± 5 | 1.09 ± 0.10 |
| 001137.25+144201.4 ...... | 0.131834 | 43.73 | 0.50 | 183 ± 7 | 1011 ± 24 | 2082 ± 78 | 399 ± 7 | 926 ± 18 | 3621 ± 35 | 1796 ± 27 | 594 ± 10 | 274 ± 4 | 0.40 ± 0.03 |
| 001416.92+145038.4 ...... | 0.206182 | 43.91 | 0.74 | 11 ± 8 | 749 ± 16 | 1465 ± 66 | 228 ± 5 | 32 ± 18 | 2050 ± 26 | 1116 ± 29 | 90 ± 7 | 358 ± 25 | 0.97 ± 0.05 |
| 001441.54+154400.5 ...... | 0.358144 | 44.12 | 0.41 | 5 ± 3 | 228 ± 10 | 1707 ± 116 | 46 ± 2 | 37 ± 9 | 773 ± 33 | 1755 ± 114 | 31 ± 6 | 244 ± 48 | 0.86 ± 0.12 |
| 001457.47—094511.0 ...... | 0.177650 | 43.23 | 0.32 | 16 ± 5 | 221 ± 12 | 1410 ± 146 | 164 ± 4 | 108 ± 10 | 964 ± 15 | 1361 ± 43 | 22 ± 3 | 294 ± 20 | 0.10 ± 0.08 |

Notes.—Col. (1), Object name in J2000.0; col. (2), redshift given by the SDSS spectroscopic pipeline; col. (3), monochromatic luminosity at 5100 Å; col. (4), featureless nuclear continuum fraction at 5100 Å; col. (5), Hβ narrow component flux; col. (6), Hβ broad component flux; col. (7), Hβ broad component FWHM; col. (8), [O ii] λ3727; col. (9), Hα narrow component flux; col. (10), Hα broad component flux; col. (11), Hα broad component FWHM; col. (12), [N ii] λ6583 flux; col. (13), [N ii] λ6583 FWHM; col. (14), optical Fe II strength relative to Hβ broad component. Table 1 is available in its entirety in the electronic edition of the *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content.

$^a$ In units of ergs s$^{-1}$

$^b$ The nuclear light fraction is unreliable for FC $\leq 0.25$.

$^c$ Observed frame line flux in units of $10^{-17}$ ergs s$^{-1}$ cm$^{-2}$.

$^d$ In units of km s$^{-1}$. 
an NLS1 galaxy is that the “broad” component of H\(\beta\) or H\(\alpha\) is detected (at the >10 \(\sigma\) confidence level) and is narrower than 2200 km s\(^{-1}\) in FWHM. This criterion resulted in 2011 NLS1 candidates, whose main spectral parameters are summarized in Table 1.

It is noticeable that our selection criterion is somewhat different from the “conventional” NLS1 definition (see § 1) in two aspects: first, the line width cutoff of 2200 km s\(^{-1}\) is slightly higher than the commonly used 2000 km s\(^{-1}\); second, we did not restrict ourselves to objects with \([\text{O} \text{ iii}]/\text{H}\beta < 3\). These modifications were made based on the following considerations: (1) The line width distribution for the Balmer lines reveals a rather smooth transition between NLS1s and BLS1s, which means that any dividing line is somewhat arbitrary and “operational.” Besides, different line profiles were used by the different authors (see VVG01 and references therein), and sometimes the narrow component was not taken into account properly (e.g., WPM02), resulting in underestimation of the line width (see § 3.2). As can be seen from Figure 4 (upper left panels), typical relative errors of the broad components of H\(\beta\) and H\(\alpha\) are 6% and 3%, respectively.

By relaxing the FWHM cutoff in H\(\beta\) or H\(\alpha\) up to 2000 km s\(^{-1}\), we could cover most of the bona fide NLS1s with low spectral quality, although at the expense of introducing a few spurious ones. Imposing the stricter criterion of FWHM \(\leq 2000\) km s\(^{-1}\) would reduce the sample size to 1885 objects. (2) The restriction of \([\text{O} \text{ iii}]/\text{H}\beta < 3\) was originally introduced to separate NLS1s from Seyfert 2 galaxies, where the resolution and/or S/N of the observed spectra were too low to do so. This is not the case for at least the majority of objects in our study, however, as discussed in § 2.1. Consequently, this criterion becomes no longer necessary. In fact, there is only one object (SDSS J104755.93+073951.2; see Fig. 5, upper panels) that fails to meet this restriction. As a serendipitous finding, one object (SDSS J113323.97+550415.8) having the prominent, narrow “broad” Balmer emission lines \([\text{FWHM}(\text{H}\beta) \sim 2100\) km s\(^{-1}\) and FWHM(H\(\alpha\)) \sim 1900 km s\(^{-1}\)] characteristic of NLS1s was actually a type 2 supernova. Its spectrum and SDSS image are shown in Figure 5 (lower panel). The object is located at the edge of the nearby blue compact galaxy UGCA 239 (SDSS J113323.46+550420.6) and has the same redshift as the galaxy. It was noticed because its brightness
decreased by \( \sim 3 \) mag within less than 1 yr between the photometric and spectroscopic observations. Its disappearance from our later imaging observation of UGCA 239 using the 2.16 m telescope of Beijing Observatory in 2005 January confirmed its supernova nature. Accordingly, we removed this object from our NLS1 sample.

### 3.2. Reliability of the Sample Parameters and Comparison with Previous Samples

Our NLS1s were drawn from a well-defined parent population of broad emission-line AGNs comprising candidates of both QSOs (Richards et al. 2002) and galaxies (Strauss et al. 2002; Eisenstein et al. 2001). Considering the fact that the vast majority of the sample were selected based on the optical selection criteria, we regard the sample simply as an optically selected sample. The emission-line parameters were measured with high accuracy by precise subtraction of the stellar and nuclear continuum and proper decomposition of the permitted emission lines into a narrow and a broad component. Since the broad components of H\( \alpha \) and H\( \beta \) were measured separately, we could check our emission-line fitting algorithm by comparing the two measurements. Figure 4, which plots FWHM(H\( \alpha \)) against FWHM(H\( \beta \)), confirms the previously known correlation between the two. Our linear fit, FWHM(H\( \alpha \)) = (0.842 \pm 0.016)FWHM(H\( \beta \)), is consistent with the FWHM(H\( \alpha \)) = 0.873FWHM(H\( \beta \)) found by Eracleous & Halpern (1994), and the 1 \( \sigma \) deviation about 10%
is only slightly larger than typical measuring errors (see inset panel). We also compared the fluxes of the broad components of Hα and Hβ and found $F(H_{\alpha}) = (3.028 \pm 0.017)F(H_{\beta})$ and a dispersion of ~0.36 in the Hα-to-Hβ ratio (Fig. 6). The good agreement between the independent measurements of the broad Hα and Hβ components indicates that our emission-line fitting algorithm should be accurate and reliable.

The method for identifying NLS1s we used in this work is largely different from that used in WPM02; moreover, the WPM02 sample was drawn merely from the “QSO” database of the SDSS early data release (EDR). It would therefore be interesting to compare our sample with that of WPM02. We found that the 150 NLS1 candidates in the WPM02 sample are all included in our parent sample of broad emission-line AGNs. Our measured FWHM(Hβ) are compared with those in WPM02 in the lower left panel of Figure 4. For those objects in which the narrow component of Hβ is negligible, we found excellent agreement between the two measurements. However, for about 1/3 of the objects, our measurements of FWHM (Hβ) are significantly larger than theirs. Going through these objects by visual inspection of their spectra revealed that the discrepancy is due to the non-negligible contribution of the Hβ narrow component, which was not taken into account in WPM02. To demonstrate this effect we plot in Figure 4 (lower right panel) the FWHM(Hβ) ratio of our measurements to theirs against the height ratio of the narrow to broad component of Hβ, taken as an indicator of the relative strength of the narrow component. It can be seen that the measured FWHM(Hβ) values in WPM02 start to deviate from ours when the narrow component becomes non-negligible, that the deviation gets worse as the narrow component increases, to reach a factor of 2 or more when the narrow component surpasses the broad component in height.

As a result, five objects in the WPM02 sample were excluded from our NLS1 sample because their FWHMs of the Hβ broad component actually exceeded our criterion of 2200 km s⁻¹. Their deblended components of Hβ and Hα resulting from our analysis are shown in Figure 7. On the other hand, our sample includes 86 objects from the EDR database that were not included in the WPM02 sample. Of these, only 17 fall within the range defined by the differing cutoffs, 2000 km s⁻¹ ≤ FWHM(Hβ) ≤ 2200 km s⁻¹, while most of these because they were assigned by WPM02 to a separate category, Seyfert 1.5, by virtue of their prominent narrow components of the Balmer emission lines. We included these simply because their broad components had FWHM(Hα) or FWHM(Hβ) that satisfied our cutoff criterion. We argue that the nature of these objects (see Fig. 8 for some examples) should not be much different from classic NLS1s, and there seem to be no particular reasons to exclude them based merely on the prominence of their narrow emission lines. In addition, thanks to our starlight–nucleus decomposition and automated spectral fitting algorithm, our sample includes 13 NLS1s drawn from the EDR Galaxy database, which was not considered in WPM02 at all; in fact, a total of 138 NLS1s were culled from the Galaxy catalog from the SDSS DR3 database. The rest few objects not included in the WPM02 sample have either low spectral quality or large uncertainties in the measured spectral parameters. We accordingly believe that our NLS1 sample has a greater degree of completeness than the WPM02 sample.

The following caveats should be noted: Given the quality $S/N \sim 10$ typical of the SDSS spectra for low-redshift broad-line AGNs (BLAGNs), objects with very narrow “broad” permitted emission lines could not be effectively identified unless the Fe ii multiplets were sufficiently strong. Also, NLS1s with large extinction may have been missed out. Observations in multi–wave bands, such as the hard X-ray band, are needed to identify such objects.

4. SAMPLE PROPERTIES

4.1. The Fraction of NLS1s

Our sample of NLS1s is more than 10 times the size of WPM02, while equally or even more complete and uniform. In this section we present some basic properties of the NLS1 population, taking advantage of this unprecedented sample size. The NLS1s as a whole make up 14% of all the broad emission-line AGNs. This fraction is consistent with the often quoted value of 15%, first suggested by Osterbrock (1988) and later confirmed by WPM02. Figure 9 shows the distribution of NLS1s and “normal” BLAGNs in redshift and nuclear luminosity (as represented by the $g$-band absolute psf magnitude), as well as the NLS1 fraction within overall BLAGNs. The NLS1 fraction appears to increase slightly up to a redshift of 0.45, after which it decreases dramatically toward high redshift. This is actually not a reflection of the cosmic evolution of the NLS1 fraction but is rather one of its dependence on the nuclear luminosity (as seen in Fig. 9), which is strongly correlated with redshift for a flux-limited sample.

The fast decrease of the NLS1 fraction with increasing nuclear luminosity in the high-luminosity range results actually from the emission line width–luminosity relation, which is discussed below in §4.2. The strong positive correlation of the NLS1 fraction with luminosity in the low-luminosity range $M_g \lesssim -22$ mag is unexpected. The fraction peaks at $M_g \sim -22$ mag, where NLS1s make up about 20% of all SDSS BLAGNs; this peak apparently results from a dip in the luminosity distribution of BLAGNs here (see Fig. 9), without there being a corresponding one in that of NLS1s. It is likely that this dip in the BLAGNs distribution is due to selection effects, in the sense that most of the low-luminosity AGNs were targeted as “galaxies,” while the high-luminosity ones were targeted as “QSOs” in the SDSS. However, we argue that the peak in the NLS1 fraction should be real because objects of both the NLS1 and BLS1 types were selected according to the same criteria in the SDSS. It may be a result of the
combination of the local black hole mass function and the distribution of the mass accretion rate. Detailed discussion on this issue is beyond the scope of this paper and will be presented elsewhere.

It was once thought that NLS1s are radio quiet; however, the past few years saw the discovery of about a dozen “radio-loud” NLS1s (Siebert et al. 1999; Grupe et al. 2000; Zhou & Wang 2002; Zhou et al. 2003). Two objects among these, both identified from the SDSS, are very radio loud (Zhou et al. 2003, 2005) according to the criterion given in Sulentic et al. (2003). The incidence of radio-loud NLS1s, or the dependence of the fraction of NLS1s on the radio properties is of particular interest. This is because radio-loud NLS1s show some extreme characteristics.

Fig. 7.—Same as Fig. 2, but for the five objects that were classified as NLS1s in WPM02 but rejected as such in this paper.
opposite to typical radio-loud AGNs, e.g., the extremely steep soft X-ray spectrum in contrast to the usual flat spectrum (Sulentic et al. 2000). This issue can be examined in more detail with our large NLS1 sample. Out of the 2011 NLS1s, 142 were detected in FIRST (the Faint Images of the Radio Sky at 20 cm survey; Becker et al. 1995). The radio detection rate is 7.1% ± 0.2%, which is significantly less than what we found for BLS1s at 10.2% ± 0.1%. It is remarkable that all the radio sources of the NLS1s detected in the FIRST were unresolved in their radio images. The distribution of radio loudness \( R \) (defined as the logarithm of the flux ratio between 1.4 GHz and the optical \( g \)-band) is shown in Figure 10 (left panels), respectively, for the NLS1s and BLS1s detected in the FIRST. Compared to the BLS1s, the radio loudness distribution of the NLS1s drops much faster beyond \( R \sim 1 \), indicating a decline of the NLS1 fraction toward high \( R \)-values. The NLS1 fraction is \( \sim 15.5% \) in radio-quiet and radio-intermediate AGNs (\( R \leq 1 \)), similar to that from other optically selected samples; it falls down to \( \sim 10% \) in moderately strong radio AGNs (\( 1 \leq R \leq 2 \)) and further down to \( \sim 5% \) in powerful radio AGNs (\( R \gtrsim 2 \)). In particular, we found only five very radio-loud NLS1s in the whole sample, including the two we reported previously, SDSS J084957.98+510829.0 and SDSS J094857.32+002225.5. These two very radio-loud NLS1s show flat spectra and dramatic variability in the radio band, indicating the presence of relativistic jets pointing toward the observer. In fact, SDSS J084957.98+510829.0 had been observed before the SDSS and was classified as a BL Lac object with a wrong redshift (Zhou et al. 2005 and references therein). For the other three sources no significant radio variability was found in time spans of several years between the NVSS (the NRAO VLA Sky Survey; Condon...
et al. 1998) and the FIRST. With a spectral index of $\alpha \approx 0.4$, the radio spectrum of the most powerful NLS1, SDSS J104732.68+472532.1, is somewhat steeper for a blazar-like source. The dependence of the NLS1 fraction on radio power (Fig. 10, right panels) is similar to that on the radio loudness. A detailed account on the radio properties of NLS1s will be presented in a forthcoming paper of the series.

Historically, X-ray surveys have been an important tool for the finding and study of NLS1s. For instance, Puchnarewicz et al. (1992) found that about 50% of their soft X-ray–selected AGNs were NLS1s; a similar result was also obtained by Grupe (2004). However, we found that the overall NLS1 fraction is only ~19.4% ± 0.8% for our optically selected sample. Plotted in Figure 11 (left panel) is the dependence of the NLS1 fraction on the soft X-ray flux density for the BLAGNs with X-ray counterparts in the RASS; it reveals a strong dependence—the NLS1 fraction increases dramatically with the X-ray flux. At the faint end, the NLS1 fraction is ~15%, similar to that found in optically selected BLAGN samples. At the bright end, it increases up to ~40%, close to that of the soft X-ray–selected AGN samples reported previously; this is where the NLS1 fractions for optically selected and soft X-ray–selected AGN are reconciled. This is not surprising, as above this high flux level optically selected and X-ray–selected BLAGN samples are largely overlapping. Interestingly, we also found a trend of decreasing fraction of NLS1s toward high X-ray luminosity (Fig. 11, right panel).

![Graphs showing redshift and luminosity distribution](image1)

![Graphs showing radio loudness and radio power](image2)
4.2. The Luminosity–Emission Line Width Relation

It has been claimed by several authors (e.g., Miller et al. 1992; VVG01) that the nuclear luminosity is correlated with the width of the broad Balmer emission lines for BLAGNs, including NLS1s. We plot in Figure 12 line luminosity versus line width for Hα and Hβ, respectively, for our sample. A weak yet significant correlation is present between the two parameters, despite the small range of the line width (the Spearman coefficient $r = 0.29$ for FWHM(Hβ) and $L$(Hβ), and $r = 0.34$ for FWHM(Hα) and $L$(Hα), corresponding to chance probabilities much less than 0.1% in both cases). The correlations appear to result from the presence of an upper boundary, as indicated by the dashed lines in Figure 12. As will be seen below, the limit is likely caused by the existence of upper limits in the accretion rate in units of the Eddington rate.

The central black hole mass can be inferred from the size and the velocity dispersion of the broad emission-line region (BLR),

$$M_{\text{BH}} \propto R_{\text{BLR}} V^2,$$

provided the BLR is virialized. We can use the width (FWHM) of the Balmer emission lines to estimate the velocity dispersion of the BLR. Supposing all AGNs have on average the same ionization parameters, the same ionizing spectral energy distribution (SED), and the same BLR densities and column densities, then we would expect a simple scaling relation between the BLR size and the monochromatic luminosity at 5100 Å (e.g., Peterson 1993),

$$R_{\text{BLR}} \propto [\lambda L(5100)]^{0.5}.$$

Fig. 11.—Dependence of the fraction of NLS1s on the X-ray flux (left panels) and X-ray luminosity (right panels).

Fig. 12.—Luminosity vs. FWHM for the broad components of the Hβ and Hα emission lines, respectively. Note that the vast majority of NLS1s populate in the region below the guiding lines (dashed lines), which represent a constant luminosity a few units of the Eddington luminosity. See § 4.2 for detailed discussion.
Hence, we can express the virial mass of the central black hole mass as

$$M_{BH} \propto [\lambda L_{(5100)}]^{0.5} [\text{FWHM}(H\beta \text{ or } H\alpha)]^2.$$  \hspace{1cm} (4)

For our NLS1s, we find that $\lambda L_{(5100)}$ is tightly correlated with the luminosity of $H\beta$ broad component, $L(H\beta)$ (Fig. 13, left panel). A linear fit yields

$$\log [\lambda L_{(5100)}] = (8.57 \pm 0.28) + (0.840 \pm 0.007) \log [L(H\beta)].$$  \hspace{1cm} (5)

Also, assuming that all objects have the same SED, we get

$$L_{bol} \propto \lambda L_{(5100)} \propto [L(H\beta \text{ or } H\alpha)]^{0.840}.$$  \hspace{1cm} (6)

Therefore, for objects emitting at the Eddington luminosity,

$$L_{bol} = L_{Edd} \propto M_{BH},$$  \hspace{1cm} (7)

a given value of $\text{FWHM}(H\beta \text{ or } H\alpha)$ corresponds to a value of $L(H\beta \text{ or } H\alpha)$,

$$L(H\beta \text{ or } H\alpha) = C[\text{FWHM}(H\beta \text{ or } H\alpha)]^{4.762}. \hspace{1cm} (8)$$

The exact value of the constant $C$ depends on the shape of the ionization continuum, the geometry and physical condition of the BLR, and the cosmology adopted. This correspondence is visualized in Figure 12 by the dashed line with the constant $C$ so chosen that $L_{bol}$ is a few units of $L_{Edd}$. It can be seen that most of our NLS1s populate below the line. This result implies that the radiation of the majority of AGNs including NLS1s cannot be much higher than a few units of the Eddington luminosity. The correlation between the broad line width and the nuclear luminosity naturally explains the decrease of the NLS1 fraction toward high luminosities reported in § 4.1.

A strong correlation between the luminosity of continuum and $[O \text{ iii}]$ emission line was also found for our NLS1s (see Fig. 13, right panel), although not as tight as the $L(H\beta) - \lambda L_{(5100)}$ correlation. The best linear fit to the data points yields

$$\log [\lambda L_{(5100)}] = (7.11 \pm 0.56) + (0.885 \pm 0.0133) \log [L_{[O \text{ iii}]}]. \hspace{1cm} (9)$$

This relation is useful for estimating the intrinsic luminosity of narrow emission-line AGNs based on $[O \text{ iii}]$ luminosity (e.g., Zakamska et al. 2003). If the central black hole mass of these type 2 AGNs can be reliably estimated, one can evaluate their mass accretion rate and search for type 2 counterparts of NLS1s in those objects with high Eddington ratios $L/L_{Edd}$.

**4.3. Broad Emission Lines**

Although not a defining property, NLS1s usually show strong optical Fe $\text{ii}$ emission lines. Out of the 2011 NLS1s, the Fe $\text{ii}$ multiplets were detected in 1787 objects at the >3 $\sigma$ level. For the rest, the SDSS spectra were too noisy to yield reliable measurements and the 3 $\sigma$ upper limits were calculated (see Table 1). The relative strength of the Fe $\text{ii}$ multiplets is conventionally expressed as the flux ratio of Fe $\text{ii}$ to $H\beta$: $R_{4570} \equiv Fe_{\text{ii}} \lambda 4434-4684/H\beta$, where Fe $\text{ii} \lambda \lambda 4434-4684$ denotes the flux of the Fe $\text{ii}$ multiplets integrated over the wavelength range of 4434–4684 Å, and $H\beta$ the flux of the broad component of $H\beta$ (e.g., VVG01). The distribution of $R_{4570}$ for the NLS1 sample is shown in Figure 14. The average is $R_{4570} = 0.82$ and the dispersion at 1 $\sigma$ is 0.37 when only the 1787 objects with reliable Fe $\text{ii}$ detection were considered. This is significantly larger than the typical value of $R_{4570} \sim 0.4$ found in normal AGNs (Bergeron & Kunth 1984). The inclusion of the nondetections would not change the results significantly, since they only account for $\sim 10\%$ of the whole sample. About a quarter of all the NLS1s are moderately strong Fe $\text{ii}$ emitters with $R_{4570} \gtrsim 1$, while this fraction is only $\sim 5\%$ in normal AGNs (Lawrence et al. 1988). We identified 17 new extreme Fe $\text{ii}$ emitters ($R_{4570} \gtrsim 2$) from the present NLS1 sample, which doubled the number of known objects of this kind (VVG01; Zhou et al. 2002; Zheng et al. 2002).

The merits of our sample are its large size and uniformity, thanks to which some weak correlations are expected to be identifiable. Hence, the sample is suited for an examination of whether the previously known correlations for broad line AGNs can be...
extended to smaller line widths. The E1 space involves primarily the correlations between three parameters: FWHM(H$\beta$), $R_{4570}$, and the soft X-ray spectral index, $\Gamma$. In Figure 15 $R_{4570}$ is plotted against the FWHM of the broad components of H$\beta$ and H$\alpha$, respectively. We found that the known anticorrelation between $R_{4570}$ and the FWHM of the broad Balmer line, although weak, continues to exist in NLS1s. The Spearman correlation coefficient is $r = -0.23$ for $R_{4570}$ versus FWHM(H$\beta$) and $r = -0.31$ for $R_{4570}$ versus FWHM(H$\alpha$), corresponding to chance probabilities of $\ll 0.1\%$ in both cases. The correlation is slightly stronger between $R_{4570}$ and FWHM(H$\alpha$) than between $R_{4570}$ and FWHM(H$\beta$); this is because, in general, the measuring uncertainties are smaller in FWHM(H$\alpha$) than in H$\beta$. Gaskell (1985) suggested that the large $R_{4570}$ in NLS1s was due to their Balmer emission lines being weak rather than their Fe $\pi$ emission being strong; this was confirmed by VVGO1 by showing a moderately strong correlation between H$\beta$ luminosity and $R_{4570}$ found in some 200 broad line AGNs including 64 NLS1s. We did not find such a correlation for NLS1s alone, however. This result indicates that NLS1s form a distinct subclass, at least as regarding those showing rather broad low-ionization lines, namely “population B” (Sulentic et al. 2000).

Interestingly, strong correlations were found between the luminosity of the Balmer emission lines and the equivalent widths of both the Balmer and Fe $\pi$ emission lines (the “inverse” Baldwin effect; see Fig. 16) for NLS1s. We do not know exactly the origin of this strong correlation, which is rather weak—if it exists at all—in BLS1s. Contamination from stellar light can be ruled out as we believe that starlight has been properly subtracted out. Either a luminosity-dependent SED, for which the optical-to-UV spectrum flattens as luminosity increases, or an increase in the covering factor of BLR with increasing luminosity, may explain such a correlation.

A strong correlation between the ROSAT photon index $\Gamma$ and FWHM(H$\beta$) has been well established for broad emission-line AGNs (Laor et al. 1997; Wang et al. 1996; Boller et al. 1996). While BLS1s show a rather small scatter in their photon indices, NLS1s show a larger dispersion of $\Gamma \sim 1$–5 (Zhou & Wang 2002). It is not yet clear whether the $\Gamma$–FWHM(H$\beta$) correlation could extend to very small Balmer line widths. A total of 635 NLS1s have X-ray counterparts in the RASS catalog; however, only a fraction have enough photon counts for an estimation of the photon index. We searched for more data from the ROSAT Source Catalog of pointed observations (RSC; Voges et al. 1999) in an attempt to improve the X-ray data quality. X-ray sources that lie within 30$''$ of the optical positions were regarded as real matches. In all, 136 RSC sources were found (all detected in the RASS) and their RSC data were used in preference to their RASS data, because of their longer exposures. Following Schartel et al. (1996) and Yuan (1998), we calculated the X-ray photon indices and X-ray fluxes using the two hardness ratios and the count rates given in the ROSAT catalogs for an assumed Galactic absorption column density.

Figure 17 plots the ROSAT photon indices $\Gamma$ versus the FWHM of H$\beta$ and H$\alpha$ for the 310 NLS1s, for which $\Gamma$ could be estimated with reasonable certainty. Of particular interest, there appears to exist a turnover in the correlation trend at FWHM around 1000 km s$^{-1}$ for both H$\beta$ and H$\alpha$. For FWHMs above the turnover (FWHM $\gtrsim 1000$ km s$^{-1}$), $\Gamma$ is significantly anticorrelated with both FWHM(H$\alpha$) and FWHM(H$\beta$); applying the Spearman test gave a correlation coefficient $r = -0.24$ and $r = -0.21$, and a chance probability of $p = 0.1\%$ and $p = 0.04\%$, for $\Gamma$–FWHM(H$\alpha$) and $\Gamma$–FWHM(H$\beta$), respectively. In the
FWHM range below 1000 km s$^{-1}$, on the contrary, the trend is reversed, with $r = 0.366$, $p = 1.7\%$ and $r = 0.316$, $p = 1.2\%$ for the $\Gamma$–FWHM(H$\alpha$) and $\Gamma$–FWHM(H$\beta$) relations, respectively. Objects with the steepest spectral slopes (the peak in the $\Gamma$ distribution) were found to have FWHM values around $\sim 1000 \text{ km s}^{-1}$. For the 61 NLS1s in the FWHM range of 800–1200 km s$^{-1}$, the mean photon index is $\langle \Gamma \rangle = 2.9 \pm 0.4$, where 43 objects ($\sim 70\%$) have $\Gamma \gtrsim 2.75$ and only two objects have $\Gamma \lesssim 2.0$.

4.4. Narrow Emission Lines

For 751 NLS1s in our sample the fluxes of the H$\beta$ narrow component could be reliably measured at the $\sim 3 \sigma$ level; for most of the rest meaningful upper limits could be obtained. We plot in Figure 18 (upper panel) the distribution of the flux ratio of [O iii] $\lambda 5007$ to the narrow component of H$\beta$, [O iii] $\lambda 5007$/H$\beta$. For those objects with only an upper limit on the H$\beta$ component, a lower limit of [O iii] $\lambda 5007$/H$\beta$ is set at 10. Objects having [O iii] $\lambda 5007$/H$\beta$ $\lesssim 5$ were found in only $\sim 15\%$ of the NLS1s of our sample, and most of those NLS1s with low [O iii] $\lambda 5007$/H$\beta$ ratios are actually "composite" objects in which a large fraction of the emission lines come from H ii regions in the host galaxies. This result is consistent with that of VVG01 but is contrary to that of Rodriguez-Ardila et al. (2000). We plot in Figure 18 (lower panel) the diagnostic diagram for the NLR of 168 NLS1s,
for which the two sets of narrow emission lines, [O iii]/Hα/C12
and [N ii]/Hα/C11
could be reliably measured. About 10% of these
NLS1s are scattered into the region occupied by star-forming
galaxies; this fraction is also consistent with that of VVG01
(6/64 in their sample). One important implication is that the
majority of the type 2 counterparts of NLS1s are actually Seyfert 2
galaxies.

Using a sample of \(~400\) broad emission-line AGNs selected
from the first data release of the SDSS, Boroson (2005) found
that the low-ionization forbidden lines ([O ii], [N ii], and [S ii]
doublets) had mutually consistent redshifts, while in about half
of the AGNs the [O iii] doublet was blueshifted with respect to
the redshift defined by the low-ionization forbidden lines.
The average blueshift of [O iii] was \(40\) \(\mathrm{km\ s^{-1}}\), and the largest shift
could reach \(\sim400\) \(\mathrm{km\ s^{-1}}\). This phenomenon also appears in our
NLS1 sample (Figs. 19a and 19b). The peaks of the [O iii] line in
\(~60\) NLS1s are shifted by \(\sim400\) \(\mathrm{km\ s^{-1}}\). The spectrum of one
such object is shown in Figure 20 (upper panel). These “blue
outliers” (Zamanov et al. 2002) can provide a valuable tool in
the study of the dynamics of NLR and its possible connection
with other AGN components.

We also found a few NLS1s showing double-peaked profiles
of narrow emission lines (Fig. 20, lower panel). Possible expla-
nations of the origin of such profiles invoke bipolar outflows, a

4.5. Notes on Other Rare Type NLS1s
One remarkable property of this large sample is its diversity.
Rarities could be readily identified, such as very radio-loud NLS1s,
“blue outliers,” and objects with double-peaked narrow emission
lines as mentioned above. Below we present several other rare
types of objects, namely “UV-deficient” NLS1s, “Fe ii-deficient”
NLS1s, and NLS1s with broad absorption line troughs (BALs).
As illustrative examples, some of their spectra are shown in Fig-
ures 21, 22, and 23. Rare type objects are very useful for exam-
ing AGN models.

It is generally believed that each NLS1 harbors a relatively
small black hole accreting at a very high accretion rate. Accord-
ing to this scenario, NLS1s would have a flat spectral shape in
the optical-to-UV band. While this was found to be indeed the
case for the majority of the sample, some NLS1s show deficient
radiation in the blue part of their SDSS spectra. Most of these
“UV-deficient” spectra can be explained as being due to heavy
extinction caused by a presumed dusty torus and/or dust lane in
the host galaxies. In a few objects, however, this unusual spec-
trum cannot be explained by extinction. For example, the UV dip
in the spectrum of SDSS J142033.7+573900.9 (Fig. 21, upper
panel) cannot be entirely accounted for by extinction because
the flux ratio of Hγ/Hβ = 0.40 ± 0.02 is close to the theoretical
value expected for a spectrum free from extinction.
Another rare class of NLS1s is concerned with the strength of the Fe\textsuperscript{II} multiplets. While the Fe\textsuperscript{II} emission lines are generally found to be strong in most NLS1s, they are very weak, or even undetectable, in some objects with very narrow “broad” Balmer emission lines (Fig. 22). The closest type to these objects is dwarf Seyfert 1 galaxies, such as NGC 4395 (e.g., Filippenko & Sargent 1989). The difference between the two classes lies in that the Fe\textsuperscript{II} deficient NLS1s found here have a relatively high luminosity with respect to the black hole mass, and hence a very high accretion rate.

NLS1s and broad absorption line (BAL) QSOs share many common observational properties (see Brandt & Gallagher 2000...
for a review). This similarity motivated several authors to investigate possible connections between the two. For instance, there is the suggestion that BAL QSOs are misaligned NLS1s (Sulentic et al. 2000). We have identified six NLS1s with possible BAL (three of the candidates were serendipitously discovered in the SDSS DR4), whose SDSS spectra are shown in Figure 23. The facts are perplexing. On one hand, BAL QSOs are thought to be otherwise normal QSOs seen nearly edge-on according to the popular unification models. On the other hand, there is convincing observational evidence for a small inclination angle for at least some NLS1s (e.g., Zhou et al. 2003). Despite the fact that many observed properties of BAL QSOs can be explained by orientation-based unification models, evidence begins to mount that polar outflows do exist, at least in some BAL QSOs (Zhou et al. 2006). It appears that the real situation is much complex than is assumed by the simple models.

5. BLACK HOLE–BULGE RELATION IN NLS1s

5.1. $M_{\text{BH}}$–$\sigma_*$ Relation

A growing body of evidence accumulated in the past decade suggests that the evolution of supermassive black holes (SMBHs) and that of their host galaxies are tightly linked. Kormendy & Richstone (1995) found that SMBH mass, $M_{\text{BH}}$, is correlated with the mass of the spheroidal component, $M_{\text{bulge}}$, in seven nearby galaxies. This relationship was later confirmed and quantified by Magorrian et al. (1998) based on a sample of 36 nearby galaxies with Hubble Space Telescope photometry and ground-based kinematics data. Ferrarese & Merritt (2000) and Gebhardt et al. (2000) demonstrated that $M_{\text{BH}}$ is tightly correlated with the stellar velocity dispersion, $\sigma_*$. Nelson et al. (2004) measured the bulge stellar velocity dispersion in 14 Seyfert 1 galaxies whose SMBH masses were determined using the reverberation mapping technique and showed that the Seyfert galaxies followed the same $M_{\text{BH}}$–$\sigma_*$ relation as nonactive galaxies. The tight correlations for both normal and active galaxies indicate that the most of the SMBH mass was built up in the past by accretion of the same gas that also formed the stars in the host galaxy spheroid. It is of particular interest as to when and how SMBH and the surrounding spheroid of stars settled down at the right masses. A straightforward approach to investigate the physical link between the SMBH growth and the bulge formation is to measure the SMBH masses and bulge properties in high-redshift AGNs and compare them with those in low-redshift AGNs and quiescent galaxies. This is a very hard undertaking given the observational difficulties. One alternative is to study young AGNs in the local universe. It has been suggested that NLS1s are normal Seyfert galaxies in their early stage of evolution, when the SMBH is growing fast via accreting mass at a high rate (e.g., Wang et al. 1996; Boller et al. 1996; Laor et al. 1997; Mathur 2000). In this sense NLS1s may serve as a surrogate for high-redshift AGNs (Wang & Lu 2001).

A direct probe of the $M_{\text{BH}}$–$\sigma_*$ relation is practically useful since, in principle, the stellar velocity dispersion of a bulge in nearby active galaxies can be determined more accurately than the bulge luminosity or compactness (Häring & Rix 2004). In practice, however, width of the [O iii] emission line is often used instead of stellar velocity dispersion due to observational difficulty of the latter. Using such an approach several groups of authors explored the $M_{\text{BH}}$–$\sigma_*$ relation for NLS1s recently, with conflicting results: Mathur et al. (2001), Grupe & Mathur (2004), Bian & Zhao (2004), and Botte et al. (2004) found that NLS1s show a systematically lower $M_{\text{BH}}/M_{\text{bulge}}$ ratio than normal broad line AGNs, while Wang & Lu (2001) and Wandel (2002, 2004) did not find a clear difference between the two. The difference may
be attributed, at least partly, to the different line widths used by the different authors. Wang & Lu (2001) argued that only the symmetric line component can trace the gravitational potential of the bulge and so they used the width of the blue-wing-subtracted [O iii] line from VVG01; in contrast, most others adopted the total [O iii] line profile. It has been shown that the [O iii] line profiles in most Seyfert galaxies are evidently asymmetric, so signifying complex kinetics of the emission line regions (VVG01 and references therein). Moreover, contamination from the Fe II emission aggravates the problem, which is especially true for NLS1s. To remove all these uncertainties from the study of the SMBH–bulge relation, it is essential to have direct measurements of \( \sigma \), instead of the [O iii] line width. The underlying physical justification is clear, since the stellar kinematics is more indicative of the bulge gravitational potential than is the gas in the NLR of the AGN. As an attempt along this line, Botte et al. (2005) obtained the near-infrared spectra of eight NLS1s with a moderately high resolution of \( \sim 50 \text{ km s}^{-1} \) per pixel and measured directly the stellar velocity dispersions using the Ca II \( \lambda 8498, 8542, 8662 \) absorption triplet. They found that \( \sigma_{\text{O III}} \geq \sigma \), for 8 of the 10 NLS1s with \( \sigma \) available so far and demonstrated that the NLS1s follow the same \( M_{\text{BH}}-\sigma \) relation as normal broad line AGNs and nonactive galaxies. However, the sample of Botte et al. (2005) is too small to give conclusive results, as the authors themselves warned. A large NLS1 sample with properly measured \( \sigma \) is utterly needed.

As discussed above in \( \S 2.2 \), in the process of decomposing the stellar and nuclear components in NLS1s, \( \sigma \), can be obtained automatically. Although the resolution and S/N ratio of the SDSS spectra are not perfect for exploring the \( M_{\text{BH}}-\sigma \) relation in NLS1s, the present sample is so large as to render it sensitive for identifying any weak trend. Apart from the spectral resolution and signal-to-noise ratio, the measurement uncertainty of \( \sigma \) is also strongly dependent on the relative contribution of the stellar light. We found that \( \sigma \) could be measured with acceptable errors for spectra with a median signal-to-noise ratio S/N \( \geq 10 \) and a relative contribution of starlight more than 40% of the total flux at 5100 Å. A small number of objects have measured \( \sigma \), values as small as \( \sigma < 50 \text{ km s}^{-1} \), which is actually beyond the resolution of the SDSS; they were discarded from the analysis. Adopting these criteria yielded 308 objects with, we believe, reasonably well-determined \( \sigma \); they formed the subsample that we used to test the black hole–bulge relation for NLS1s. Figure 24, for this subsample, the estimated \( M_{\text{BH}} \) versus \( \sigma \), with the \( M_{\text{BH}} \) determined using the line width–luminosity mass scaling relation (e.g., Kaspi et al. 2000; McLure & Jarvis 2002; Dietrich & Hamann 2004),

\[
\frac{M_{\text{BH}}}{M_\odot} = 4.82 \times 10^6 \left[ \frac{L_\odot(5100)}{10^{44} \text{ erg s}^{-1}} \right]^{0.7} \left[ \frac{\text{FWHM}(H\beta)}{1000 \text{ km s}^{-1}} \right]^2.
\]

The well-known \( M_{\text{BH}}-\sigma \) relation for normal galaxies, as parameterized by Tremaine et al. (2002),

\[
\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = (8.13 \pm 0.06) + (4.02 \pm 0.32) \log \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right).
\]

is marked in the plot by the dashed line. A correlation is clearly present, which follows the trend of the \( M_{\text{BH}}-\sigma \) relation for galaxies (the Spearman correlation coefficient \( r = 0.27 \) giving a chance probability of \( p = 2 \times 10^{-6} \)). Meanwhile, the data points of NLS1s show a systematic downward shift relative to the relation for galaxies as defined in equation (5), with the bulk of the subsample (~90%) located below the dashed line. The results indicate that, first, the correlation between \( M_{\text{BH}} \) and \( \sigma \) remains valid for NLS1s; and second, the SMBHs in NLS1s are underweight and their growth lags behind the formation of the bulges, as suggested by e.g., Mathur et al. (2001). We stress that our results are actually consistent with Botte et al. (2005); their much smaller sample prevented the authors from drawing the same conclusion. In fact, only 2 of the 10 NLS1s in their sample are located above the \( M_{\text{BH}}-\sigma \) line for normal galaxies and normal AGNs.

Caution should be exercised when accepting the above results, considering that the derived \( \sigma \) may be affected by contamination by the rotation of the galactic disk. This issue presents a matter of concern here since, for NLS1s at typical redshifts in our sample, the fiber aperture would cover the whole galactic disk. For a further examination of the reality of the \( M_{\text{BH}}-\sigma \) relation obtained above, we tried to minimize the contamination effect of the galactic disk rotation. We visually inspected the SDSS images of NLS1s at redshifts <0.1 with directly measured \( \sigma \), and picked out objects for which either the host galaxies appear to be face-on or the 3′ fiber aperture is dominated by the galactic bulge contribution. This selection yielded 33 objects; their SDSS images are shown in Figure 25. For these objects, we believe that the contamination of the disk, even if significant, should not lead to overestimation of \( \sigma \). Their \( M_{\text{BH}}-\sigma \) relation is plotted in Figure 26. It can be seen that the same trend of correlation persists, and all the data points are distributed well below the expected \( M_{\text{BH}}-\sigma \) relation for galaxies of Tremaine et al. (2002).

5.2. \( \sigma \)--Narrow Line Width Relation

Since we have relatively good measurements of \( \sigma \), for the subsample, we could use them as a standard calibrator to test potential correlations with the width of any narrow emission lines. This has practical potential in the sense that in many NLS1s,
Fig. 25.—Montages of 33 NLS1s with redshift less than 0.1, for which either the host galaxies are viewed face-on or the SDSS 3″ fiber aperture is dominated by the bulge contribution.
especially luminous ones, the measurement of \( \sigma_* \) is not available, that maybe the line width could serve as a good surrogate. Below we test the previously reported relations between \( \sigma_* \) and FWHM of the [N \text{ ii}] and [O \text{ iii}] lines. We plot in Figure 27 the FWHM[N \text{ ii}] values (deconvolved to remove the effect of the SDSS spectral resolution) versus \( \sigma_* \), for 240 out of the 308 NLS1s, for which the [N \text{ ii}] doublet is detected at the \( >10 \) \( \sigma \) level. A significant correlation was found at a probability level \( p = 1.8 \times 10^{-11} \) (the Pearson correlation test). The objects were found to be distributed almost symmetrically with respect to the often quoted relation FWHM[N \text{ ii}] \( \approx 2.35 \sigma_* \), with a 1 \( \sigma \) deviation of \( \approx 30\% \) (Fig. 27, solid line). The result indicates that the [N \text{ ii}] emission line can be used as a surrogate for stellar velocity dispersion in NLS1s. We extended the above test to a larger sample of Seyfert 2 galaxies compiled from the SDSS, comprising some 3000 objects with high spectral S/N ratios. A correlation is found very similar to that for the NLS1s (Fig. 28). A linear fit yielded FWHM[N \text{ ii}] \( \sim 2.62 \sigma_* \), as compared to the often quoted FWHM[N \text{ ii}] \( \sim 2.35 \sigma_* \). We conclude that, for Seyfert 2 galaxies, FWHM[N \text{ ii}] can also be used as a surrogate of \( \sigma_* \). We find that, after taking all the scatter into account, FWHM[N \text{ ii}] can predict black hole masses to within a factor of 3.

In comparison, the [O \text{ iii}]-\( \sigma_* \) correlation is only marginal. Our result suggests that the [O \text{ iii}] line width, which has been widely used in the literature, is actually not a good indicator of the \( \sigma_* \) and, hence, of the black hole mass. In fact, this is not unexpected considering that, in more than half of the NLS1s in our sample, the [O \text{ iii}] lines have complex profiles. In a systematic investigation of the stellar and gaseous kinematics in narrow emission-line AGNs, Greene & Ho (2005) also noted the different behavior...
of the low-ionization lines and [O iii] and pointed out that $\sigma_{[O \text{ iii}]}$ cannot be directly used to replace $\sigma$. Using a two-component Gaussian fit to the [O iii] line profiles, the authors found that the core of the [O iii] line could trace $\sigma$, statistically but with a considerable scatter. This approach, however, cannot yield meaningful results for most of the objects in our sample because of the low S/N ratio and/or the effect of the residuals of the Fe ii emission in their SDSS spectra.

Having established the good FWHM[N ii]$–\sigma$ relation, we can extend the above examination to the black hole–bulge relation by making use of FWHM[N ii]. The advantage of so doing is that, compared to $\sigma$, FWHM[N ii] is much easier to measure and is available for a larger number of NLS1s. In Figure 29, we plot $M_{\text{BH}}$ versus FWHM[N ii] for 613 NLS1s with reliably measured FWHM[N ii]. A correlation is present, but there is a systematic deviation from the equivalent relation expected for galaxies given by Tremaine et al. (2002) transformed from FWHM[N ii] = 2.35 $\sigma$ (dashed line). The results confirm those obtained above for a smaller sample by making direct use of $\sigma$ (Fig. 24).

6. CONCLUSIONS AND PROSPECTS

6.1. Summary of Conclusions

We have systematically analyzed the spectroscopic data from the QSO and galaxy database in the SDSS DR3. After proper subtraction of the stellar and nuclear continua as well as the Fe ii multiplets, prominent emission lines were carefully modeled and measured with typical relative errors less than 10%. A large sample of ~2000 NLS1s has been selected based on a simple well-defined criterion: the presence of a “broad” component of the H/β (or Hα) line with FWHM $\lesssim$ 2000 km s$^{-1}$. The present sample outnumbers previous NLS1 samples by a factor of ~10. Taking advantage of such an unprecedented large and uniform sample with accurately measured spectral parameters, we carried out various statistical analyses, some of which were possible only for the first time.

Overall, the often quoted frequency $\sim$15% is confirmed for finding NLS1s in optically selected broad emission-line AGNs; meanwhile, the frequency is also found to be strongly dependent on the optical luminosity. The fraction of NLS1s peaks around $M_g \sim$ −22 mag (the SDSS $g$-band absolute magnitude) and drops quickly toward both the high- and low-luminosity ends. We interpret the lower chance of finding NLS1s in high-luminosity AGNs as a result of an imposed upper limit on the Eddington ratio ($L/L_{\text{Edd}}$) of a few units. The smaller fraction in the low-luminosity range may arise from the combination of two factors: the shape of the SMBH mass function and the distribution of the accretion rate. Low-luminosity NLS1s contain a very small SMBH mass accreting at a very high rate, which are rare in the local universe. We do not confirm the previous results that $\sim$50% of soft X-ray (e.g., ROSAT) selected AGNs are NLS1s. Such a fraction is found only for X-ray bright AGNs but drops quickly with decreasing soft X-ray flux. The frequency of finding NLS1s in faint ROSAT AGNs ($\lesssim$10$^{-12.5}$ erg s$^{-1}$ cm$^{-2}$ in the 0.1–2.4 keV band) is actually the same as in optically selected AGNs. The dependence of the NLS1 fraction on the soft X-ray luminosity shows the same trend as on the optical luminosity, and the fraction peaks around $\sim$10$^{43.2}$ ergs s$^{-1}$. Deeper X-ray surveys than the RASS are needed to pin down the exact peak luminosity. Moreover, we find that the NLS1 fraction is also strongly dependent on the radio loudness and the radio luminosity. The frequency of finding NLS1s in radio-quiet AGNs (with logarithmic radio-to-optical flux ratio $R < 1$) is $\sim$15%, similar to that for optically selected AGNs. This value drops to $\sim$10% in moderately strong radio AGNs ($1 < R < 2$), and further down to $\sim$5% in powerful radio AGNs ($R > 2$).

We find that on average the relative strength of the Fe ii emission ($R_{\lambda570}$) in NLS1s is about twice that in normal AGNs; $R_{\lambda570}$ is anticorrelated with the width of the broad component of the Balmer emission lines. The well-known correlation between the width of the broad low-ionization line and the soft X-ray spectral slope is found to hold true for NLS1s in general; in addition, it shows some quite peculiar behavior: $P$ is anticorrelated with FWHM(H/β) in the range FWHM(H/β) $\gtrsim$ 1000 km s$^{-1}$, then the trend is reversed in the range FWHM(H/β) $\sim$ 1000 km s$^{-1}$. We find that the equivalent width of the H/β and Fe ii emission lines are strongly correlated with the H/β and the continuum luminosity. We do not find any difference in the NLR properties between NLS1s and normal AGNs. About 10%–20% of NLS1s show abnormally low line ratios of [O iii] to the narrow component of H/β, which is a result of the contribution of H/regions in the host galaxies. Blue shifts of the [O iii] emission line were found in about half of the NLS1s, similar to that in normal AGNs.

 Stellar velocity dispersions $\sigma$ could be measured within statistically meaningful uncertainties for 308 NLS1s. For this subsample we examined the $M_{\text{BH}}−\sigma$ relation for NLS1s. We found that the black hole mass is also significantly correlated with the stellar velocity dispersion; however, the bulk of the NLS1s have black hole masses statistically smaller than expected from the $M_{\text{BH}}−\sigma$ relation for normal galaxies and AGNs. These results support the hypothesis that NLS1s are underbeamed AGNs, and the growth of their SMBH lags behind the formation of the galactic bulge. With a typical relative error $\sim$30%, the line width of [N ii] is found to be a better indicator of $\sigma$, than that of [O iii]. By using a larger subsample with reliably measured FWHM[N ii], the $M_{\text{BH}}$–bulge relation for NLS1s was further examined and similar results were obtained.

6.2. Remarks on Future Work

Limited by the scope of the this paper, most of the analyses presented above are only phenomenological. Systematic and detailed investigations based on this large data set of some of the interesting aspects as outlined in § 1 are just underway. For instance, we have initiated a program to study the X-ray spectral and temporal properties of the NLS1s in our sample by making use of archival serendipitous data from ROSAT, XMM-Newton, and Chandra. The multiwavelength SED can be constructed and studied by compiling data from the existing archives in various wave bands. The present results on the $M_{\text{BH}}−\sigma$ relation for NLS1s are only statistically meaningful; observations with higher spectral resolution and S/N ratios are needed for more precise results. Moreover, mounting evidence accumulated in the past decade indicates that the AGN phenomena and the star formation history are closely linked; the preliminary result on the $M_{\text{BH}}−\sigma$ relation for NLS1s may represent an important link in the sequence of galaxy evolution. In this direction, we are going to study the stellar content of the host galaxies in the hope of finding any clues to the starburst–AGN connection.

Some peculiar objects of various rare types have been identified in our NLS1 sample, namely, very radio loud NLS1s, [O iii] “blue outliers,” double-peaked narrow line emitters, UV-deficient NLS1s, and BAL NLS1s. Detailed studies of their properties, which are expected to be useful for constraining AGN models, will be addressed in forthcoming papers.

In the above and other related studies of NLS1s, a major source of uncertainty comes from the determination of the black hole masses. Mass estimation using a one-epoch spectrum is subject to large uncertainties (cf. Vestergaard 2004); reliable measurements
of the SMBH mass are limited to only a few NLS1s so far, however. With interest we noted that a few percent objects in our NLS1 sample have duplicated observations in the SDSS, some of which show large amplitude variability (see Fig. 30). This property presents us a great potential of measuring the black hole masses of NLS1s by making use of the much more accurate reverberation mapping technique. We plan to monitor an NLS1 sample with a moderate size to select candidates and then to carry out the reverberation mapping. The work will also enable us to explore the dynamics of the BLR for NLS1s.

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