TYPE 2 COUNTERPARTS OF NARROW-LINE SEYFERT 1 GALAXIES

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ABSTRACT

Unified models of Seyfert galaxies, based on viewing angles, successfully explain the observed differences between type 1 and 2 Seyferts. The existence of a range in accretion rates ($\dot{m} \sim 0.001 - 1$) relative to the Eddington rate (from broad-line Seyfert 1s to narrow-line Seyfert 1s or NLS1s) and the unification of Seyfert galaxies imply that there must be type 2 counterparts of NLS1 galaxies i.e., Seyfert 2s with high accretion rate or small black hole mass. One such Seyfert 2, NGC 5506, has already been unmasked based on near infra-red spectroscopy. Here we confirm the above result, and present evidence for two additional type 2 counterparts of NLS1s based on XMM-Newton observations. The three AGNs NGC 7314, NGC 7582 and NGC 5506, with a type 1.9/2 optical spectrum, show extremely rapid variability by factors $> 2.4$, $\sim 1.3$, and $\sim 1.7$ in 200 s, 350 s and 300 s, respectively, and steep $2 - 12$ keV spectrum ($\Gamma \gtrsim 2$) in their intrinsic X-ray emission, characteristic of NLS1 galaxies. These observations establish the ‘obscured NLS1 galaxies’ as a subclass of Seyfert 2 galaxies.

Subject headings: accretion, accretion disks – galaxies: active – X-rays: galaxies

1. INTRODUCTION

Seyfert 1 galaxies exhibit a large range in their observed characteristics e.g., the FWHM of the H$\beta$ line in the range of $\sim 1000 - 10000$ km s$^{-1}$, X-ray variability timescale from a few hundred seconds to years, the soft (0.1 – 2 keV) and hard (2 – 10 keV) X-ray photon indices in the range of $\sim 1.0 - 4.0$ and $\sim 1.5 - 2.5$, respectively, etc. The Seyfert 1s with extreme properties, i.e. $FWHM_{H\beta} \lesssim 2000$ km s$^{-1}$, steepest X-ray spectra and rapid X-ray variability form a distinct subclass known as narrow-line Seyfert 1 galaxies (NLS1s). The standard unification scheme of Seyfert galaxies supposes that the central engines of Seyfert 1s and 2s are basically the same, and the differences in their observed properties are due to different viewing angles. In Seyfert 2s, our line of sight passes through a cold torus which obscures the broad line region and the accretion disk (Antonucci 1993). Now it has been established that Seyfert 1 galaxies span a large range $\sim 0.001 - 1$ in their relative accretion rates, NLS1s lying at the higher end of the relative accretion rate distribution (Pounds et al. 1995). These facts imply that there must be Seyfert 2s with high relative accretion rates similar to those of NLS1s i.e., the type 2 counterpart of NLS1s. These objects are largely missing at present due to the difficulty in isolating them using the conventional observational techniques of the optical regime. The only way to distinguish them is to use observations which are not affected by absorption such as near infra-red spectroscopy, optical spectropolarimetry and X-ray emission above 2 keV.

In this Letter, we present X-ray evidence for three type 2 counterparts (NGC 7582, NGC 5506 and NGC 7314) of NLS1s. NGC 7582 is a classical Seyfert 2, with well defined [O III] cone (Sosa-Brito et al. 2001; Aretxaga et al. 1999; Storchi-Bergmann & Bonatto 1991). Aretxaga et al. (1999) observed NGC 7582 in an unusual optical state during July 1998 when it showed broad components of H$\alpha$, H$\beta$ ($FWHM \sim 12000$ km s$^{-1}$) blue-shifted by $\sim 2500$ km s$^{-1}$. The flux state was relatively high during the optical event, and then decreased gradually to its typical type 2 state in October 1998. Aretxaga et al. (1999) examined three scenarios: capture of a star by a super-massive black hole, a reddening change in the surrounding torus, and the radiative onset of a Type IIn supernova in the nuclear regions. These authors raise serious concerns with the first two models, and favor the SN theory to explain the broad lines. BeppoSAX study showed that X-ray emission from NGC 7582 is consistent with the Seyfert 2 nature, and a single component dominates the $2 - 100$ keV band (Turner et al. 2000). Changes in nuclear X-ray flux appeared to be uncorrelated to the gradual decline in the optical flux noted after the high state of July 1998. NGC 5506 ($z = 0.0065$) has been classified as a Seyfert 2 (de Robertis & Osterbrock 1986). Sluder (1980) reported to have found a weak, broad component to Hα. However, both Veron et al. (1980) and Whittle (1985) found no such component. Nagar et al. (2002) discovered a broad ($FWHM < 2000$ km s$^{-1}$) O I 1268/1274 µm line and the 1 µm Fe II lines in the near-IR spectrum of NGC 5506, thus unmasking an ‘obscured NLS1 nucleus’ in a Seyfert 2. Bianchi et al. (2003) presented the recent X-ray history of NGC 5506, the overall picture consists of a nucleus absorbed by cold gas with $N_H \sim 10^{22}$ cm$^{-2}$ and surrounded by a Compton-thick torus. NGC 7314 has an optical spectrum and has fluxes typical of a Seyfert 2 (Morris & Ward 1988; Winkler 1992; Joguet et al. 2001). An HST spectrum of the nuclear region of NGC 7314 revealed broad component of Hα, consistent with a Seyfert 1.9 classification (Hughes et al. 2003). NGC 7314 is well known for its rapid, large amplitude X-ray variability (Turner et al. 1987; Yaqoob et al. 1996). Yaqoob et al. (2003) detected variable, redshifted narrow lines from He-like and H-like iron using Chandra HETG spectrum of NGC 7314.

2. OBSERVATIONS & DATA REDUCTION

The three AGNs were observed with XMM-Newton. NGC 7582 was observed for ~ 20 ks on 25 May 2001 us-
Among the three AGNs, NGC 7314 shows the most remarkable rapid variability throughout the observation. The most extreme event occurred around 35500 s after the start of the observation, the count rate increased by 1.25 ± 20 counts s⁻¹ within just 300 s.

The remarkably rapid variability mentioned above are even more extreme intrinsically. The 2 – 12 keV X-ray emission from Seyfert 1.9/2 galaxies consists mainly of two components: (i) absorbed primary continuum, and (ii) Compton reflection from distant cold material. The reflection component is relatively steady over timescales of years. The 2 – 10 keV emission from Compton-thick Seyfert 2s is almost entirely Compton reflection emission, while both primary and Compton reflection emission contribute to the X-ray emission from Compton-thin Seyfert 2s. Below we estimate these contributions with spectral modeling.

4. X-RAY SPECTRA

In the following analysis we consider the time-averaged EPIC PN and MOS spectra of NGC 7582 and PN spectra of NGC 7314. We did not use the MOS data for NGC 7314 due to the high signal-to-noise of the PN data and slight mismatch in the continuum shapes inferred from the PN and MOS data. The spectra were binned to a minimum of 20 counts per channel and analyzed with XSPEC 11.3. Only the data above 2 keV are considered here. A detailed study of the complex soft X-ray emission is beyond the scope of this Letter, and has no significant impact on the final results.

The X-ray spectra of a Seyfert 2s generally show signatures of reprocessed emission; namely a strong iron Kα line at ~ 6.4 keV and a corresponding absorption edge at ~ 7.1 keV. In view of these features, we adopt a baseline model consisting of a heavily absorbed power-law, a Compton reflection component from neutral material and a narrow Gaussian to represent the iron Kα line. For the sake of completeness, we also added a second Gaussian line to describe the iron Kβ line from neutral iron. The energy and strength of the Kβ line were fixed at their theoretical values of 7.06 keV and 10% of the strength of the corresponding Kα line, respectively. All the components were modified by the Galactic column, listed in Table 1. We used the reflection model pexrav (Magdziarz & Zdziarski 1995). This model calculates the reflected spectrum from a neutral disk exposed to an exponentially cutoff power-law continuum. The pexrav model was set to produce the reflected emission only, while the power-law was set to provide the primary continuum. We fix the cutoff energy of the primary power law at 100 keV, disk inclination at 60 deg, and the abundance of heavy elements at the solar value. The free parameters are the photon index and the normalization of the primary power law, and the relative amount of reflection compared with the directly viewed primary spectrum ($R$). We also varied the intrinsic absorption column ($N_{H}^{\text{intrinsic}}$), the line energy ($E_{F,\alpha}$), and the flux ($f_{E,\alpha}$) of the iron Kα line. The baseline model resulted in a good fit ($\chi^2 = 361.2$ for 330 degrees of freedom (dof) for NGC 7582 and $\chi^2 = 1335.0$ for 1424 dof for NGC 7314). The best-fit parameters are listed in Table II and the
unfolded spectra and deviations are shown in Figures 2 (NGC 7582) and 3 (NGC 7314). The contribution of the Compton reflection component, including the narrow iron lines, to the observed X-ray flux in the 2 – 12 keV band is 48.8% for NGC 7582 and 14.1% for NGC 7314.

A comparison of ASCA (Xue et al. 1998), BeppoSAX (Turner et al. 2000) and XMM-Newton observations of NGC 7582 reveals a continuous increase in the absorption column (ΔN_H ~ 8 × 10^{23} cm^{-2}) and the 2 – 10 keV photon index (Γ ~ 0.9) from 1994 to 2001. NGC 7582 was in the lowest flux state during the XMM-Newton observation in May 2001. The observed 2 – 10 keV flux (∼ 4 × 10^{-12} erg cm^{-2} s^{-1}) is a factor ~ 5 lower than that observed with the BeppoSAX in the same band. We cannot confirm the broad asymmetric iron Kα line from NGC 7314 detected with ASCA (Yaqoob et al. 1996). XMM-Newton is not suitable to detect the multiple, redshifted narrow iron lines present in the Chandra HETG spectrum (Yaqoob et al. 2003). The best-fit photon index (Γ ~ 2.2) to the XMM-Newton data is similar to that derived from the BeppoSAX data (Γ ~ 2.1; Risaliti 2002). NGC 5506 was observed simultaneously with XMM-Newton and BeppoSAX between February 1 and 3, 2001. A joint spectral analysis of the two data sets was performed by Matt et al. (2001). The best-fit model to the PN and PDS data was similar to the baseline model except for an additional broad Kα line from ionized iron. The primary power-law was steep (Γ = 1.98±0.02) and heavily absorbed (N_H = 3.44_{-0.12}^{+0.13} × 10^{22} cm^{-2}). Using the best-fit parameters derived by Matt et al. (2001), we estimated that the contribution of the Compton reflection including the unresolved Kα line from neutral iron is 17.6% to the total observed X-ray emission (f_X = 6.76 × 10^{-11} erg cm^{-2} s^{-1}) in the 2 – 12 keV band, while the absorption corrected contribution is 14.4% to the intrinsic X-ray emission (f_X = 8.28 × 10^{-11} erg cm^{-2} s^{-1}) in the 2 – 12 keV band.

5. INTRINSIC X-RAY VARIABILITY

To estimate the variability amplitudes of the primary power-law, we have corrected the observed count rates for the contribution of the Compton reflection and heavy obscuration. First, we converted the count rates into absorbed power-law flux using a conversion factor between the time-averaged count rate and observed flux, and the contribution of the reflection emission as derived from the spectral modeling. The absorbed power-law flux were

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### Table 1: Best-fit Parameters

| Parameter | NGC 7582 | NGC 7314 |
|-----------|----------|----------|
| N_H^{int} (10^{20} cm^{-2}) | 1.93(f) | 1.46(f) |
| R | 1.84±0.46 | 2.83±0.44 |
| i | 60 deg(f) | 60 deg(f) |
| N_H^{int} (10^{22} cm^{-2}) | 89.0±6.8 | 1.05±0.14 |
| Γ | 2.20±0.14 | 2.19±0.14 |
| E_{F-Kα} (keV) | 6.41±0.01 | 6.38±0.04 |
| σ(eV) | 10(f) | 10(f) |
| f_{F-Kα} (10^{-5} photons cm^{-2} s^{-1}) | 1.87±0.2 | 1.39±0.34 |
| EW(eV) | 521±139 | 147±112 |
| E_{F-Kβ}(keV) | 7.96 | 7.96(f) |
| σ(eV) | 10(f) | 10(f) |
| f_{F-Kβ} (10^{-5} photons cm^{-2} s^{-1}) | 0.19 | 0.14 |
| EW(eV) | 66 | 18 |
| f_{ref} a | 2.76 | 7.20 |
| f_{PL} a | 2.89 | 3.69 |
| f_{int} a | 2.77 | 7.20 |
| f_{int} + a | 24.4 | 40.8 |

*Observed or intrinsic flux in units of 10^{-12} erg cm^{-2} s^{-1}.

### Table 2: 2 – 12 keV Count Rate and Unabsorbed Power-law Flux During the Most Rapid Variability Events.

| Object | Elapsed time (s) | Count rate (counts s^{-1}) | unabsorbed PL flux (erg cm^{-2} s^{-1}) |
|--------|-----------------|-----------------------------|----------------------------------------|
| NGC 7582 | 5700 ± 50 | 0.35 ± 0.05 | 3.37 ± 0.46 × 10^{-11} |
| 5900 ± 50 | 0.16 ± 0.03 | 0.28 ± 0.28 × 10^{-11} |
| 14300 ± 50 | 0.34 ± 0.03 | 3.21 ± 0.49 × 10^{-11} |
| 14900 ± 50 | 0.18 ± 0.02 | 0.60 ± 0.32 × 10^{-11} |
| NGC 5506 | 5500 ± 50 | 4.43 ± 0.17 | 5.22 ± 0.26 × 10^{-11} |
| 5850 ± 50 | 5.32 ± 0.19 | 6.58 ± 0.29 × 10^{-11} |
| 6000 ± 50 | 4.50 ± 0.17 | 5.34 ± 0.25 × 10^{-11} |
| NGC 7314 | 35350 ± 50 | 2.53 ± 0.13 | 1.91 ± 0.14 × 10^{-11} |
| 35650 ± 50 | 3.78 ± 0.16 | 3.24 ± 0.13 × 10^{-11} |

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Fig. 2.— Top: Unfolded EPIC PN X-ray spectrum of NGC 7582 and best-fit spectral model consisting of an absorbed power-law, Compton reflection and iron K lines. Bottom: Deviations, in units of sigma, of the observed data from the best-fit model.

Fig. 3.— Same as Fig. 2 but for NGC 7314.

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TABLE 1

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|-----------|----------|----------|
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| R | 1.84±0.46 | 2.83±0.44 |
| i | 60 deg(f) | 60 deg(f) |
| N_H^{int} (10^{22} cm^{-2}) | 89.0±6.8 | 1.05±0.14 |
| Γ | 2.20±0.14 | 2.19±0.14 |
| E_{F-Kα} (keV) | 6.41±0.01 | 6.38±0.04 |
| σ(eV) | 10(f) | 10(f) |
| f_{F-Kα} (10^{-5} photons cm^{-2} s^{-1}) | 1.87±0.2 | 1.39±0.34 |
| EW(eV) | 521±139 | 147±112 |
| E_{F-Kβ}(keV) | 7.96 | 7.96(f) |
| σ(eV) | 10(f) | 10(f) |
| f_{F-Kβ} (10^{-5} photons cm^{-2} s^{-1}) | 0.19 | 0.14 |
| EW(eV) | 66 | 18 |
| f_{ref} a | 2.76 | 7.20 |
| f_{PL} a | 2.89 | 3.69 |
| f_{int} a | 2.77 | 7.20 |
| f_{int} + a | 24.4 | 40.8 |

*Observed or intrinsic flux in units of 10^{-12} erg cm^{-2} s^{-1}.

TABLE 2

| Object | Elapsed time (s) | Count rate (counts s^{-1}) | unabsorbed PL flux (erg cm^{-2} s^{-1}) |
|--------|-----------------|-----------------------------|----------------------------------------|
| NGC 7582 | 5700 ± 50 | 0.35 ± 0.05 | 3.37 ± 0.46 × 10^{-11} |
| 5900 ± 50 | 0.16 ± 0.03 | 0.28 ± 0.28 × 10^{-11} |
| 14300 ± 50 | 0.34 ± 0.03 | 3.21 ± 0.49 × 10^{-11} |
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then converted to unabsorbed power-law flux using the best-fit photon indices and the absorption columns (see Table 1). The count rates and the unabsorbed power-law flux at the beginning and the end of the rapid variability events are listed in Table 2. The 2 – 12 keV unabsorbed flux of the primary power law varied by a factor $\gtrsim 2.4$ or a change in flux, $\Delta f > 1.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in 200 ± 71 s in the case of NGC 7582. A change in the intrinsic power-law flux $\Delta f = (1.36 \pm 0.37) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in 250 ± 71 s has been observed from NGC 5506. A similar change, $\Delta f = (1.33 \pm 0.19) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in 300 ± 71 s, is evident from NGC 7314.

6. DISCUSSION

We have studied the temporal and spectral characteristics of three obscured Seyfert galaxies. NGC 7582 showed a factor of two variability in the 2 – 12 keV count rate or a change of 2 – 12 keV intrinsic luminosity, $\Delta L > 9.3 \times 10^{41}$ erg s$^{-1}$ of the primary emission in just $\sim 200$ s. NGC 5506 showed a change in the count rate of 0.89 ± 0.25 counts s$^{-1}$ or a change in the luminosity of $\Delta L = (1.1 \pm 0.3) \times 10^{42}$ erg s$^{-1}$ in an interval of 250 s only. NGC 7413 showed a change in the count rate of 1.25 ± 0.20 counts s$^{-1}$ or a change in the intrinsic primary luminosity $\Delta L = (6.7 \pm 0.9) \times 10^{41}$ erg s$^{-1}$ in the 2 – 12 keV band. These are the most extreme rapid variability events ever observed from Seyfert 1.9/2 galaxies. Application of the efficiency ($\eta$) limit: $\eta > 4.8 \times 10^{-43} \Delta L / \Delta t$ (Fabian 1979), however, shows that the these events do not violate the limit for a Swarzschild black hole. Among the radio-quiet AGNs, the most rapid X-ray variability on timescales of a few hundred seconds is observed from NLS1s (see e.g., Boller et al. 1996; Leighly 1999a). The rapid X-ray variability observed from NGC 7582, NGC 5506 and NGC 7314 are similar to that of NLS1s.

In addition to the extreme variability, the three AGNs show steep 2 – 12 keV primary power-law (NGC 7582: $\Gamma = 2.26^{+0.14}_{-0.17}$, NGC 5506: $\Gamma = 1.98^{+0.05}_{-0.02}$, NGC 7314: $\Gamma = 2.19^{+0.09}_{-0.06}$). These photon indices are steeper than the mean index, $\Gamma = 1.79 \pm 0.01$, of the $\sim 300$ keV intrinsic power-law for 20 bright Compton-thin Seyfert 2s (Risaliti 2002). The photon indices are also steeper than the mean index of 1.78 ± 0.11 for the broad-line Seyfert 1s but similar to the mean index $\Gamma = 2.19 \pm 0.10$ for NLS1s in the sample of Leighly (1999b).

The similarity of the extreme variability and steep primary power-law emission of the three obscured Seyfert galaxies and that of NLS1s strongly suggests that the accretion disk-black hole system, responsible for the primary X-ray emission, is similar in the above two types of Seyfert galaxies. Many of the observed characteristics of NLS1s are interrelated e.g., the width of the H$\beta$ line is anti-correlated with the soft $(0.1 – 2$ keV) and hard $(2 – 10$ keV) power-law photon indices (Boller et al. 1996; Brandt, Mathur & Elvis 1997). Thus if the central engines of NLS1s and that of NGC 7582, NGC 5506 and NGC 7314 are similar, then permitted optical lines from the BLR should be narrower ($FWHM < 2000$ km s$^{-1}$), similar to that of NLS1s. Indeed, the discovery of near-IR permitted O I 1287$\mu$m line ($FWHM < 2000$ km s$^{-1}$) and 1 $\mu$m Fe II lines by Nagar et al. (2002) is fully consistent with the X-ray nature of NGC 5506. The dramatic appearance of broad Balmer lines in the optical spectrum of NGC 7582 in July 1998 is not expected from an obscured NLS1. However, the broad lines may not be related to the AGN, as the evolution of H$\alpha$ line width closely resembled with that of SN 1988SZ (Aretxaga et al. 1999). A near infra-red spectrum of NGC 7582 during its typical type 2 state will further clarify its nature.

In view of the above results, we suggest that the type 1/2 AGNs NGC 7582, NGC 5506 and NGC 7314 are the type 2 counterpart of NLS1 galaxies. As NLS1s form a special subclass of Seyfert 1 galaxies due to their extreme characteristics, the Seyfert 1.9/2s with extreme X-ray characteristics form a special subclass of Seyfert 2s, and we term them as “obscured NLS1” galaxies to better reflect their nature. The existence of obscured NLS1s is consistent with the standard unification of Seyfert galaxies. However, the presence of NLS1 nuclei in both type 1 and 2 Seyferts requires a new parameter, the relative accretion rate, to be incorporated in the standard unification scheme based on the viewing angle.

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