INDECENT EXPOSURE IN SEYFERT 2 GALAXIES: A CLOSE LOOK

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ABSTRACT

NGC 3147, NGC 4698, and 1ES 1927+654 are active galaxies that are classified as Seyfert 2s, based on the line ratios of strong narrow emission lines in their optical spectra. However, they exhibit rapid X-ray spectral variability and/or little indication of obscuration in X-ray spectral fitting, contrary to expectation from the active galactic nucleus (AGN) unification model. Using optical spectropolarimetry with LRIS and near-infrared spectroscopy with NIRSPEC at the W. M. Keck Observatory, we conducted a deep search for hidden polarized broad Hα and direct broad Paβ or Brγ emission lines in these objects. We found no evidence for any broad emission lines from the active nuclei of these galaxies, suggesting that they are unobscured, completely “naked” AGNs that intrinsically lack broad-line regions.

Key words: galaxies: active – galaxies: individual (NGC 3147, NGC 4698, 1ES 1927+654) – galaxies: Seyfert – polarization

1. INTRODUCTION

The “unification model” (UM) of Seyfert galaxies proposes that Seyfert 1 (S1) and Seyfert 2 (S2) galaxies are basically the same type of objects viewed from different directions (Antonucci 1993). In an S1 nucleus, our view of the central engine is relatively unobstructed, allowing a direct observation of the ionizing continuum and broad-line region (BLR). In an S2 nucleus, however, this view is blocked by some form of obscuration, most often thought of as an optically thick torus, so that any broad emission lines (BELs) and ionizing continuum are not directly visible. While this UM has enjoyed considerable success over the years and is undoubtedly correct for many Seyfert galaxies, questions regarding its universal applicability remain (see, e.g., Wang & Zhang 2007). Of particular interest is if there exists a “true” type of S2 that lacks a BLR, and whose appearance is unchanged regardless of orientation. The existence of such true or “naked” S2s has been implicated both observationally (Tran 2001, 2003; Panessa & Bassani 2002; Boller et al. 2003; Nicastro et al. 2003; Hawkins 2004) and theoretically (Nicastro 2000; Laor 2003; Czerny et al. 2004; Elitzur & Shlosman 2006; Elitzur & Ho 2009; Cao 2010). It would be of great interest to show definitively that such objects do exist in nature. Recently, a growing number of active galactic nuclei (AGNs), including NGC 3147, have been suggested to be just such objects (Gliozzi et al. 2007; Bianchi et al. 2008; Panessa et al. 2009; Shi et al. 2010).

In this Letter, we explore three of the best candidates for such a type of naked S2s: NGC 3147 (Pappa et al. 2001; Terashima & Wilson 2003; Bianchi et al. 2008), NGC 4698 (Pappa et al. 2001; Georgantopoulos & Zezas 2003), and 1ES 1927+654 (Boller et al. 2003). X-ray observations with ASCA, ROSAT, XMM-Newton, and Chandra show that all three exhibit characteristics typical of a type-1 view of the active nucleus: little or no intrinsic X-ray absorption from spectral fitting, high hard X-ray to [O III] ratios indicating low obscuration (Bassani et al. 1999), and in the case of 1ES 1927+654, rapid, persistent, and strong X-ray variability observed over a 12 yr timescale. In addition, they are all classified as Compton thin, consistent with little or no intrinsic absorption above Galactic column density (∼10^20–10^21 cm^−2). Thus, all indications appear to show that we have an unobscured, direct view of these active nuclei. Yet, optically they are classified as low-luminosity S2s, with no discernible sign of broad Balmer emission lines in their spectra (Ho et al. 1997; Boller et al. 2003). Table 1 summarizes the observed and derived optical and X-ray properties of the galaxies. Given the type-1 view inferred from the X-ray observations, the lack of BELs in these objects is puzzling and in apparent contradiction with the UM of AGNs. We have therefore conducted a deep search for any weak or hidden BELs in these objects using optical spectropolarimetry and near-infrared (near-IR) spectroscopy. Deep spectropolarimetry was designed to target Hα to look for any scattered, polarized broad-line component, or hidden broad-line region (HBLR), and near-IR spectroscopy was used to probe deeper through any obscuration to directly uncover any broad permitted lines, such as Paβ and Brγ, as has been done by, e.g., Veilleux et al. (1997). This Letter reports the main results of this search.

2. OBSERVATIONS AND DATA REDUCTION

Spectropolarimetric observations were made with the low-resolution imaging spectrograph (LRIS; Oke et al. 1995) and polarimeter on the Keck I telescope at the W. M. Keck Observatory (WMKO). We used a long, 1″ wide slit centered on the nucleus of the AGN. For NGC 4698 and 1ES 1927+654, multiple observations were made similar to that described in Tran (2010) over two different epochs to improve the signal-to-noise ratio (S/N) and to look for any evidence of variability. No variability was detected, and the results presented here are the sum average for all observations over all epochs for each object. The total exposure times in Table 2 represent some of the deepest spectropolarimetric observations for this type of objects, typically ∼10× deeper than any previous surveys (see, e.g., Tran 2003). Spectropolarimetric reduction was done with standard techniques, as described in Tran (1995).

Near-infrared spectroscopic observations were made with NIRSPEC (McLean et al. 1998) on the Keck II telescope at WMKO in the low-resolution mode with the 42″ × 0″57 or 0″76 slit. The telescope was dithered in an ABBA pattern, and nearby A0 V stars (39 UMa, 55 Dra, HD 111744, and HIP 62745) were observed to correct for telluric absorption and relative flux calibration. Data reduction was initially performed with

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the REDSPEC\textsuperscript{1} package for flat fielding, spectral rectification, wavelength calibration, and spectral extraction. Exposures from different nod positions were used for sky subtraction and then co-added. Individual exposures range from 240 s to 900 s and different nod positions were used for sky subtraction and then wavelength calibration, and spectral extraction. Exposures from each object is shown in Table 2.

We then used the routine xtellcor_general (Vacca et al.\textsuperscript{2} 2003) within the Spextool package (Cushing et al.\textsuperscript{2} 2004) to perform telluric correction and relative flux calibration. Table 2 presents the log of observations.

3. RESULTS AND DISCUSSION

We show in Figure 1 the results of the optical spectropolarimetry, and in Figure 2 those of the near-IR spectroscopy. Table 3 summarizes the polarimetric characteristics of the objects. The main spectropolarimetric result is that in each of the objects, although a small polarization is detected, no polarized broad Hβ is seen. Note that the polarizations listed in the table are the observed values, uncorrected for galactic host starlight dilution. With typical galaxy fractions of ∼90%, the intrinsic polarizations are ∼1%–3%. The small measured polarizations appear intrinsic to each galaxy, as the Galactic interstellar polarizations are probably insignificant due to their relatively high Galactic latitudes (Table 3). Moreover, no narrow emission lines are visible in the polarized flux spectra, indicating that any polarization imposed outside of the host galaxies is negligible. They belong to the class of non-HBLR S2s (Tran \textsuperscript{2}2003). The non-detection of HBLRs is secure, confirming similar results of Shi et al. (2010) for NGC 3147 and NGC 4698. HBLRs have been successfully detected in sources with comparable weakly polarized continuum such as NGC 2110 (Tran \textsuperscript{2}2010).

Likewise, although the S/N is excellent in the near-IR spectroscopy, there is no detection of any of the broad permitted hydrogen lines such as Paβ or Brγ. The near-IR spectra are dominated by the underlying host stellar continuum, with strong absorption band heads due to CO, but essentially no emission lines are detected. This is very similar to the near-IR spectra of some objects in the atlas of Riffel et al. (2006), such as NGC 1144 and NGC 1097.

\begin{table}[h]
\centering
\caption{Optical and X-ray Characteristics\textsuperscript{a}}
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Object & Type & z & \(m_B\) & \(f_{\text{[OIII]}}\) & \(\text{Hα}/\text{Hβ}\) & \(N_H\) & \(f_{2–10\text{keV}}/f_{\text{[OIII]}}\) & \(\log(M_{\text{BH}})\) & \(\log(L_{\text{bol}}/L_{\text{Edd}})\) \\
\hline
NGC 3147 & Sey 2 & 0.0094 & 11.4 & 17.2 & 5.23\textsuperscript{c} & 1.5 \times 10^{21} & ∼40 & 8.64 & −3.05 \\
NGC 4698 & Sey 2 & 0.0034 & 11.2 & 3.12 & 5 \times 10^{20} & 1–3 & 7.43 & −3.39 \\
IES 1927+654 & Sey 2 & 0.019 & 15.4 & 3.16 & 4.15\textsuperscript{d} & 7.3 \times 10^{20} & ∼800\textsuperscript{e} & 7.34 & −2.23 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Journal of Observations}
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Object & UT Date & Instrument & Total Exposure & Slit & Filter & \(\lambda\) Range \\
\hline
NGC 3147 & 2003 Jun 28 & LIRSp & 4×900 & 1′ & ⋯ & 6000–9800 Å \\
 & 2010 Feb 25 & NIRSPEC & 3600 & 42″ × 0.76 & N-3 & 1.15–1.35 μm \\
 & 2010 Feb 25 & NIRSPEC & 1600 & 42″ × 0.76 & K & 2.00–2.43 μm \\
NGC 4698 & 2003 Jun 28 & LIRSp & 2×(4×900) & 1′ & ⋯ & 6000–9800 Å \\
 & 2004 Jun 17 & LIRSp & 4×1200 & 1′ & ⋯ & 4650–7200 Å \\
 & 2005 May 24 & NIRSPEC & 2880 & 42″ × 0.76 & N-3 & 1.15–1.35 μm \\
 & 2010 Feb 25 & NIRSPEC & 2400 & 42″ × 0.76 & K & 2.00–2.43 μm \\
IES 1927+654 & 2003 Jun 28 & LIRSp & 2×(4×1200) & 1′ & ⋯ & 6000–9800 Å \\
 & 2004 Jun 17 & LIRSp & 4×1200 & 1′ & ⋯ & 4650–7200 Å \\
 & 2004 May 31 & NIRSPEC & 1920 & 42″ × 0.57 & N-3 & 1.15–1.35 μm \\
 & 2004 Jul 21 & NIRSPEC & 2880 & 42″ × 0.57 & K & 2.00–2.40 μm \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Spectropolarimetric Results}
\begin{tabular}{|c|c|c|c|c|}
\hline
Object & \(b_n\) & \(E(B–V)\) & \(p_{\text{max}}\) & \(\theta\) \\
\hline
NGC 3147 & 39.5 & 0.024 & 0.31 ± 0.01 & 159 ± 1 \\
NGC 4698 & 71.3 & 0.026 & 0.11 ± 0.01 & 64 ± 3 \\
IES 1927+654 & 21.0 & 0.088 & 0.26 ± 0.02 & 88 ± 2 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{a} Galactic latitude.
\textsuperscript{b} Galactic interstellar reddening from NED. The maximum Galactic interstellar polarization, \(p_{\text{max}}\) obeys the relation \(p_{\text{max}} \leq 9E(B–V)\) (Serkowski et al. 1975).
\textsuperscript{c} Observed average over the wavelength range 6050–7100 Å.

\textsuperscript{1} http://www2.keck.hawaii.edu/inst/nirspec/redspec.html
We now examine why we do not see any BELs given the naked nature of these AGNs, which we shall refer to as the “naked non-HBLR S2s” (NNHS2s). The possible explanations include: (1) highly obscured AGNs that are misclassified as Compton thin, (2) different obscuration in the X-ray and optical (objects may be X-ray-unobscured but are actually highly obscured optically), (3) variable BELs due to either changes in the nuclear engine or to obscuring material moving in and out of our line of sight, (4) hidden narrow-line S1 galaxies (NLS1s), and (5) low-powered AGNs with weak or absence of BLRs. We discuss below each possibility in turn.

1. All three NNHS2s in this Letter are classified as Compton thin due to their low column densities \( N_H \lesssim 10^{21} \) cm\(^{-2}\), derived from X-ray spectral fitting. In addition, the hard X-ray to [O III] flux ratio \( f_{2-10keV}/f_{[OIII]} \), a good measure of the nuclear X-ray obscuration (Bassani et al. 1999), is comfortably above unity, the usual dividing line between

Figure 1. Spectropolarimetry of NGC 3147, NGC 4698, and 1ES 1927+654. Top: rotated Stokes parameter (RSP), essentially a measure of the polarization in percent; middle: total flux spectrum \( (F_\lambda) \); bottom: the polarized or Stokes flux spectrum \( (S \times F_\lambda) \). The flux scales are in units of \( 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\) A\(^{-1}\). The position of H\(\alpha\) is marked. In each object, a small amount of polarization is detected but no polarized broad lines indicative of an HBLR are seen in the polarized flux spectra.

Figure 2. Normalized J- and K-band spectra of NGC 3147, NGC 4698, and 1ES 1927+654. In each case, the expected positions of Pa\(\beta\) (left) and Br\(\gamma\) (right) are marked as dotted vertical lines. The spectra are dominated by galactic starlight, and we do not detect any emission in Pa\(\beta\) or Br\(\gamma\). No direct BELs are present.
Compton-thin and Compton-thick cases (see Table 1). This is similar to the ratio in S1s, where it is typically ~20 with a range between about 1 and 300 (Bassani et al. 1999; Akylas & Georgantopoulos 2009), again consistent with little intrinsic absorption.

Recently Shu et al. (2010), using higher spatial resolution XMM-Newton observations, find that the X-ray emission from the naked S2 candidate NGC 7590 is actually dominated by extended off-nuclear sources, leading them to conclude that this galaxy is actually Compton thick rather than X-ray unobscured as previously thought. If a similar situation applied to the NNHS2s in this study, then they could also be misclassified as X-ray unobscured. However, all three objects, NGC 3147, NGC 4698, and 1ES 1927+654, have been extensively studied with high-resolution Chandra and XMM-Newton observations (e.g., Boller et al. 2003; Georgantopoulos & Zezas 2003; Terashima & Wilson 2003; Bianchi et al. 2008; Brightman & Nandra 2008; Akylas & Georgantopoulos 2009; Shi et al. 2010), and the unabsorbed nature of their nuclear X-ray emission appears to be well confirmed, with no confusion from external sources. In addition, temporal variation in the X-ray flux has been observed in both NGC 3147 (Terashima & Wilson 2003) and 1ES 1927+654 (Boller et al. 2003), implying that the X-ray flux is not scattered from a heavily obscured nucleus. Thus, all three objects in this study appear to be genuinely naked S2s.

2. Studies have shown that the X-ray and optical nuclear absorption in AGNs are often mismatched (see review by Maiolino & Risaliti 2007). The reason may be that the X-ray and optical absorbers are not cosmatically aligned. Some Seyfert galaxies are known to undergo extreme changes in X-ray column density $N_H$, perhaps due to the gaseous absorbing material crossing the line of sight to the X-ray source, as seen in, e.g., NGC 1365 (Risaliti et al. 2007). The observed rapid $N_H$ variability has constrained the X-ray absorber location to the scale of the BLR. The size scale of the nuclear optical absorber, however, is probably much larger than the dust sublimation radius or beyond the BLR. As a result, it is common to find, for example, Compton-thick AGNs that are seemingly optically unobscured, with type-1 BELs (Maiolino & Risaliti 2007).

Could the objects in this study be the Compton thin but optically thick AGNs? This could be similar to the class of X-ray bright optically normal galaxies (XBONGs), which are strong in X-ray, but optically dull, leading to the suggestion that they may be optically obscured by large-scale dust in the host galaxy (Rigby et al. 2006). For the objects in this study the extinction inferred from the X-ray column density is only $A_V \sim 0.2$–0.68 assuming the Galactic relationship between $N_H$ and $A_V$ of Gorenstein (1975). If they were obscured by galactic-scale dust similar to XBONGs, they may be expected to show much higher extinction in the narrow-line region (NLR). However, as Table 1 shows, the narrow-line Balmer decrements are fairly normal, yielding at most an optical extinction of $A_V \leq 1.6$, indicating that heavy large-scale dust obscuration cannot explain the lack of BLR in these galaxies. If typical broad permitted lines were present, their complete absence in both the optical and near-IR implies that the extinction must be of order $A_V \sim 11$–26 (Veilleux et al. 1997), entirely inconsistent with observations. While it is possible that the gas to dust ratio $N_H/A_V$ could be anomalously low in these galaxies, leading to a preferentially higher absorption in the optical, it cannot explain this discrepancy. Although we cannot rule out such heavy obscuration in the BLR itself, it seems unlikely.

The absence of any narrow lines in the polarized flux spectrum also indicates that the scattering region must be interior to the NLR. The scattering region may be very compact, as in the hidden double-peaked emitters (HDPEs) NGC 2110 and NGC 5252, lying between the NLR and BLR (Tran 2010), such that it could still be obscured from the line of sight. However, if this were the case, we would not expect to see any polarized light. The fact that we see any scattered light at all suggests that the scattering region, however small, is intercepted, and that the lack of any BELs suggests that there may be very little or no BLR gas, or that the scatterers are within the BLR.

3. Changes in the central engine or the obscuration could result in changes in appearance of the AGN. For example, NGC 2110 and NGC 5252 were originally classified as non-HBLR S2s, but perhaps due to their intrinsic broad-line variability, later found to be HDPEs (Tran 2010). Could the objects in this study be similar to such objects? This is unlikely since multiple observations intended to look for such variability failed to find any. For NGC 3147 and NGC 4698, there is an additional spectropolarimetric epoch reported by Shi et al. (2010), who also failed to detect any HBLRs. While more follow-up observations may be required to definitively rule out variability, the present data do not favor such scenario.

Another cause of changes in classification would be for optically obscuring clouds to pass in front of the line of sight, changing the appearance of the objects (e.g., Tran et al. 1992). This type of changes typically occurs over very long timescales, of order years or decades. Since all available published data over many years show no evidence for the appearance or disappearance of BELs in any of the objects, we do not favor this interpretation for the lack of HBLR in these NNHS2s.

4. Could the NNHS2s be the hidden counterparts to the NLS1s, as suggested by, e.g., Dewangan & Griffiths (2005), Zhang & Wang (2006), Wang & Zhang (2007), and Haas et al. (2007)? This can be ruled out by the simple observation that no emission lines of any kind, broad or narrow, are seen in the polarized flux spectra. In addition, one defining characteristic of NLS1s is the strong Fe II emission (Osterbrock & Pogge 1985), but none is observed in the polarized light of these NNHS2s. Polarized Fe II emission has been detected in other HBLR S2s (Tran et al. 1999). To be sure, the hidden NLS1s envisioned by Zhang & Wang (2006) and Wang & Zhang (2007) are thought to be those with high X-ray absorption, not the X-ray unobscured type discussed here.

5. The most likely scenario that can explain the lack of BELs is that NNHS2s represent true S2s with very little or virtually no BLR. These are the low-luminosity AGNs, probably powered by radiatively inefficient or advection-dominated accretion flow (ADAF), that intrinsically lack BLRs, as suggested observationally by, e.g., Tran (2001, 2003), Bianchi et al. (2008), Panessa et al. (2009), and Shi et al. (2010), and inspired theoretically by Nicastro

\[ \text{We assume, as in other Seyfert galaxies, that the detected polarizations come from scattering of light by an anisotropic medium such as a bi-cone.} \]
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(2000), Laor (2003), Elitzur & Shlosman (2006), Elitzur & Ho (2009), and Cao (2010). They could be at the dead and dying endpoint in the evolutionary path envisioned by Wang & Zhang (2007; their “unabsorbed non-HBLR S2s B” designation). As suggested by Wang & Zhang (2007), these could be the gas-poor, and dust-rich galaxies, which after undergoing vigorous star formation and accreting matter at a high rate have exhausted all their fuel and torus material and are now lying dormant and naked. Note that this would naturally lead to the low gas-to-dust ratio discussed above.

Since there is a well-known luminosity–BLR size relationship in AGNs (see, e.g., Denney et al. 2010), the low luminosities of the NNHS2s may lead to BLRs that are exceptionally small, resulting in lines that are too wide to be detectable (Laor 2003). We note, however, that it is possible to detect hidden extremely broad lines (FWHM up to \( \sim 26,000 \text{ km s}^{-1} \)) in objects with brightness and continuum polarization levels comparable to those in this study (Ogle et al. 1997; Tran 2010). Another key point in the theoretical models mentioned above is that the BLR is unable to form once the AGN luminosities or accretion rates become too low to support outflows from the accretion disk. The critical accretion rate at which the BLR is expected to disappear is \( L_{\text{bol}}/L_{\text{Edd}} \sim 0.001 \) (e.g., Nicastro et al. 2003; Cao 2010), with a weak dependence on the black hole (BH) mass. We use the measured \([\text{O}]\) FWHM (403 km s\(^{-1}\)) and luminosity to estimate the BH mass \( M_{\text{BH}} \) and accretion rate \( L_{\text{bol}}/L_{\text{Edd}} \) for 1ES 1927+654, using the method outlined in Wang & Zhang (2007). These quantities are listed in Table 1 along with those for NGC 3147 and NGC 4698, which are obtained from the literature (e.g., Wang & Zhang 2007). Given the uncertainties in estimating \( M_{\text{BH}} \) and \( L_{\text{bol}} \), the uncertainties in \( \log(L_{\text{bol}}/L_{\text{Edd}}) \) is \( \sim 0.5 \) dex. As the table shows, all of the accretion rates are consistent with being below the minimum threshold needed to support BLRs. Thus, the lack of BLRs in these NNHS2s can be entirely attributed to the feeblesness of their central engines.

Similarly, a significant fraction of the XBONGs can also be explained by such lethargy in their nuclear activity (Trump et al. 2009). The NNHS2s, especially 1ES 1927+654 because of its high X-ray-to-optical flux ratio, could very well be the local population of these XBONGs. In addition, there is evidence that many Fanaroff–Riley I radio galaxies are also missing hidden BLRs (see review by Antonucci 2011), and thus they could potentially be the corresponding low accretion-powered radio-loud population of NNHS2s. We note that there is also another class of AGNs with “anemic” BLR (Shemmer et al. 2010), but these appear to be different from the NNHS2s discussed here because they are powerful quasars at higher redshifts with much higher accretion rates.

4. SUMMARY AND CONCLUSIONS

NGC 3147, NGC 4698, and 1ES 1927+654 are three S2s with an unusual combination of properties: X-ray spectra show variability and little absorption indicative of a type-1 (direct) view, but optical spectra show only narrow emission lines, typical of a type-2 (obscured) view of the nucleus. A deep search for hidden BLR using Keck LRIS spectropolarimetry and direct near-IR spectroscopy with NIRSPEC does not reveal any BELs, hidden or direct. If typical broad lines were present, their non-detections would indicate an extinction of \( A_V \sim 11–26 \), inconsistent with the “naked” nature of these galaxies. While the obscuration may be due to different material for X-ray and optical light, it appears plausible that the BLRs in these objects are anemically small or absent, due to the weakness of their active central engines.

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Facilities: Keck:1 (LRISp), Keck:II (NIRSPEC)

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