The spectroscopic properties of the objects that came to be called Narrow-Line Seyfert 1s were first systematically described and named as such 15 years ago by Osterbrock & Pogge (1985). At the time, they were a relatively rare and peculiar subclass of Seyfert galaxies. Their discovery in large numbers in X-ray surveys, however, has elevated them to a role as important members of the AGN family, ones which may hold many keys to understanding the physics of AGN across the electromagnetic spectrum. This contribution reviews the spectral classification of the narrow-line Seyfert 1s, and describes some of the properties that make this unusual class of objects interesting.

1 Narrow-Line Seyfert 1s

“This unusual object merits further observations...”
Davidson & Kinman (1978)

On the possible importance of Markarian 359

The discovery of a new class or subclass of astronomical objects almost never begins with the “definitive” paper, since that paper is more often than not the outcome of a more systematic investigation into previous reports that some objects might be interesting. So too with narrow-line Seyfert 1s (NLS1s).

The watershed year in the prehistory of NLS1s is 1978. Davidson & Kinman (5) described the unusual and potentially important spectral properties of Markarian 359. Mrk 359 has a Seyfert 1-like spectrum with unusually narrow permitted lines; the FWHM of Hβ was 520±100 km s⁻¹, comparable to what is seen in classic Seyfert 2s. The second curiosity of 1978 was Mrk 42. Koski (14) and Phillips (21) remarked that Markarian 42 had many of the spectral properties of Seyfert 1s, but that the Fe II and H I lines were very narrow, like in Seyfert 2s.

In 1983, Osterbrock & Dahari (16) undertook a systematic classification of a sample of Seyferts and candidate Seyferts, and noted in their tables that four
showed unusual properties, namely “narrow H I and Fe II ... Fe II strong” (Mrk 493), and “Very narrow H I ... but noticeably wider than [O III]” (Mrk 783). It was work that led Don Osterbrock to undertake a systematic search for and study of those objects which, along the lines first noted by Davidson & Kinman, had all the basic spectral characteristics of Seyfert 1s but unusually narrow permitted lines. It was this project that Don invited me to join as a new graduate student at UC Santa Cruz in 1984. The rest, as they say, is history...

In Osterbrock & Pogge (18), we defined NLS1s to be those galaxies whose nuclear spectra are generally like those of Seyfert 1s (strong Fe II, [O III] relatively weak compared to the Balmer lines), but with line widths much narrower than typical Seyfert 1s. The formal spectral classification criteria for NLS1 galaxies that has emerged since are:

- Narrow permitted lines only slightly broader than the forbidden lines.
- [O III]/Hβ < 3, but exceptions are allowed if there is also strong [Fe VII] and [Fe X] present, unlike what is seen in Seyfert 2s.
- FWHM(Hβ) < 2000 km s⁻¹.

The first two criteria are from our original classification (18), while the maximum line-width criterion was introduced by Goodrich (8) in his spectropolarimetric study.

The essence of the classification is shown graphically in Figure 1, which contrasts an NLS1 against Seyfert 1s and 2s. While the Hβ line of the NLS1 Mrk 42 is not much wider than the Seyfert 2 Mrk 1066, the other spectral lines, especially [O III] and Fe II, appear in about the same proportions, if with narrower Fe II widths, as they do in Seyfert 1s like NGC 3516.

2 I Zw 1 and the Elusive Type 2 QSOs

“So, What is 1E0449.4–2834 Anyway?”

Halpern, Eracleous, & Forster (1998)

NLS1s appear to have analogs among the more luminous QSOs, so-called narrow-line QSOs. The prototype of the narrow-line QSOs is arguably I Zw 1 (15). The luminosity of I Zw 1 places it at the ragged boundary between the most luminous Seyfert 1s and the least-luminous QSOs, an arbitrary dividing line set at MB = −23 mag (27). Sargent (25) had noted as early as 1968 that I Zw 1 had unusually strong Fe II emission. Phillips (19; 20) made landmark studies of the Fe II lines in this object, assisted both by their strength and by the fact that the lines were sufficiently narrow that you could definitively identify the components of line blends that are otherwise just undifferentiated
emission “humps” in normal Seyfert 1s or QSOs. The unusually narrow lines of I Zw 1’s were not lost on others, for example Oke & Lauer (17) who in 1979 commented that “I Zw 1 is not a typical type 1 Seyfert since the permitted and forbidden lines are of comparable breadth”.

The first connection between NLS1s and objects like I Zw 1 was made by Halpern & Oke (12) in their 1987 study of Mrk 507 and 5C3.100. They were drawn to these objects by their unusually large X-ray luminosities compared to other Seyfert 2s. Their superior spectra showed that these objects were, in fact, not Seyfert 2s, but rather had spectra like I Zw 1 (strong Fe II and narrow permitted lines). This made them NLS1s with luminosities near the high-end of the range for Seyfert 1s. This paper is also notable in that they are the first to call attention to the possible importance of NLS1s as X-ray sources.
The story of the original Seyfert 2 classification of Mrk 507 and 5C3.100 is instructive. The earlier spectra showed the strong narrow Hβ and [O III] lines, but the Fe II lines were lost in the noise; hence they were thought to be Seyfert 2s. Halpern & Oke’s better spectra showed the Fe II lines clearly, removing their Seyfert 2 assignment. Similarly, Schmidt & Green (27) rejected Mrk 684 from their list of bright QSOs in 1983 because it had “narrow emission lines, such as those observed in Seyfert 2 galaxies”. Don and I re-observed this object and noted (18) that in fact Mrk 684 was an NLS1 with “strong Fe II emission and weak or nonexistent forbidden lines.” The false classification of objects as Seyfert 2s because of poor signal-to-noise ratio masking either weak Fe II or weak broad lines (or both) has been a persistent problem. Nowhere is this kind of classification confusion more chronic than in the long and so far fruitless search for QSO analogs of the Type 2 Seyferts; objects with QSO luminosities but Seyfert 2-like spectra (i.e., no broad lines). At issue is whether the full range of spectral properties found among lower luminosity AGN like Seyferts is recapitulated at higher luminosities.

Every now and then a preprint or paper comes to my attention that declares that such and such an object is the “first” Type 2 QSO. For a long time I would dutifully write down its name and citation on an unused corner of my office blackboard and wait. Sure enough, eventually a paper by Jules Halpern and his collaborators would come along presenting a deeper, lower noise spectrum and reclassifying the object as either an NLS1 (e.g., IRAS 20181−224 (6; 11), AXJ0341.4−4453 (26; 10)) or an intermediate Seyfert galaxy with weak broad lines (e.g., 1E0449.4−1823 (2; 13)). I called it my “Jules Just Says No” list. So far, Jules and collaborators are ahead.

Why is this? On the technical side is the inescapable fact of spectrophotometry that signal-to-noise ratio matters. Poor spectra give poor (or even wrong) classifications. Further, Seyfert 2s are not just characterized by narrow emission lines, but also by a conspicuous absence of weak broad lines or Fe II emission. Detection of these requires good spectra; the characteristic narrow lines are the easy part of the observation. On the scientific side is the possibility that true Type 2 QSOs are extremely rare, so rare that after nearly 4 decades of AGN research there is not yet a definitive example that hasn’t eventually been reclassified with better spectroscopy. The operative word here is “yet”, since the search continues regardless; rarity has its attractions, and these appear to be among the rarest of the rare. So far what it tells us is that the differences between Seyferts and QSOs are not simply a matter of luminosity.

This brings up the issue of how to classify AGN. The division of AGN into Type 1 and Type 2 is based on well-defined and well-established spectral criteria. While we hope that our classification has the virtue of relating to the underlying physics of AGN, which relation is still imperfectly understood, it is still fundamentally empirical in nature. This should be obvious, but there has
been a new fashion of late among some astronomers to call heavily obscured QSOs “Type 2 QSOs”, even though their spectra do not have the characteristics of Seyfert 2s (i.e., narrow permitted and forbidden lines, high-excitation line ratios, etc.). A dusty QSO is a dusty QSO, it is not a Type 2 QSO unless its optical spectrum satisfies the spectral criteria of a Seyfert 2.

3  X-Rays and the ROSAT Renaissance

“X-ray selection may be an efficient way to find narrow-line Seyfert 1 galaxies.”

Stephens (1989)

Sally Stephens’ PhD dissertation at UCSC was a spectroscopic study of 65 X-ray selected AGN. Of these, 10 were NLS1s, or ~15%, leading to the quote above taken from the abstract of her paper (28). Subsequent work by Puchnarewicz and collaborators found ~50% (22; 23) of their ultra-soft X-ray selected AGN were NLS1s. In hindsight, an examination of the spectra of AGN found in the HEAO-1 survey of Remillard et al. (24) and the Einstein MSS of Gioia et al. (7) found roughly similar proportions of NLS1s among them, if they were unrecognized as such at the time.

The first indication I had that Sally’s comment was truly prophetic was at the 1993 IAU Symposium 159 in Geneva. There Dirk Grupe showed me his poster paper (9) describing the results of a follow-up study of 40 new Seyferts discovered in the ROSAT All-Sky Survey. Grupe et al. found that ~50% of the RASS soft X-ray selected AGN were NLS1s. In that same year, Boller et al. (1) inaugurated the “ROSAT Renaissance” in the study of NLS1s with their seminal paper on the truly outlandish X-ray variability of IRAS 13224−3809. This NLS1 with strong Fe II emission increased in 0.1−2.4 keV brightness by a factor of 4 with an unheard of (for Seyferts) doubling time of 800 seconds! Not only are NLS1s common in soft X-ray selected samples, they are among the most variable AGN known outside of extreme objects like blazars.

In 1996 the ROSAT team effectively assumed ownership of the NLS1 class. In their important paper of that year, Boller, Brandt, & Fink (3) published their results for a study of 46 NLS1s, about half of which were X-ray discovered. This paper demonstrated the remarkable soft X-ray properties of NLS1s:

- Wide range of 0.1−2.4 keV photon indices, \( \Gamma \approx 1 − 5 \), compared to ~ 2.1 for typical Seyfert 1s.
- Rapid, high-amplitude X-ray variability (doubling times of minutes to hours).

While some NLS1s have the steepest soft X-ray excesses yet observed, it is clear from Figure 8 of Boller, Brandt & Fink (3) that not all NLS1s are ultra-soft
excess sources. A number of spectroscopically classified NLS1s have photon indices more typical of the general run of Seyfert 1s. A soft X-ray excess is a common, but not defining, characteristic of NLS1s. Searching for ultra-soft X-ray sources has proven to be an excellent way to find new NLS1s, but it is biased against NLS1s with harder 0.1–2.4 keV X-ray spectra. While the demographics of NLS1s among AGN in general is still poorly understood, the sense I get is that despite their abundance in soft X-ray surveys they are still relative rarities in general (see papers by Grupe and Hasinger herein).

4 Lies, Damned Lies, and Principal Components Analysis

“They clearly demonstrate that the Seyfert phenomenon is not a simple one-parameter effect.”

Osterbrock & Pogge (1985)

Determining the role of NLS1s within the AGN phenomenon may be approached observationally by understanding where they fall among the statistical properties of the entire class. In this regard NLS1s again display their remarkable propensity for seeking out extremes. In Boroson & Green’s landmark 1992 study of the emission-line properties of low-redshift QSOs (4), their Principal Components Analysis (PCA) revealed two convincing eigenvectors among a variety of emission-line and continuum measurements for 87 QSOs in the BQS catalog with $z < 0.5$. The second eigenvector is essentially a relatively weak H$\beta$ Baldwin Effect. The principal eigenvector, the so-called Boroson & Green Eigenvector 1, is stronger but its underlying physical basis has proven more elusive.

The principal driver behind Eigenvector 1 is a strong anticorrelation between the strengths of the Fe$\text{II}$ and [O III]$\lambda$5007 emission lines. Additional contributions come from a correlation between the FWHM of H$\beta$ and the peak of [O III]. At one extreme end of AGN along Eigenvector 1 are those objects with the strongest Fe$\text{II}$, the weakest [O III], and the narrowest H$\beta$ lines; all of which are the defining spectral characteristics of NLS1s.

Statistically speaking, PCA is a blunt instrument, a mathematical bellum omnes contra omnium among many different measurements in the hope that the ultimate physical driver of the phenomenon under study will be revealed in the principal eigenvector. It is not yet clear to me that the Boroson & Green Eigenvector 1 has lived up to this expectation, but it is interesting that NLS1s are all clustered at one extreme end of this eigenvector. What is this trying to tell us? I don’t know, but at the very least the properties of the NLS1s forcefully demonstrate that AGN are not a one-parameter family of objects. NLS1s look superficially like Seyfert 1s, but their many unusual and extreme properties are clearly telling us that they are more than just Seyfert 1s with
narrow lines.

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References
