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Peaked sources and narrow-line Seyfert 1s: A love story

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Abstract

The first similarities between peaked sources (PS) and narrow-line Seyfert 1 (NLS1) galaxies were noticed already 20 years ago. Nowadays, it is known that several sources can share both classifications, and that part of the parent population of γ-ray emitting NLS1s could be hiding among PS. In this brief review, we describe how and why this orientation-based unification was developed. We also show how the recent discovery of absorbed radio jets in NLS1s basically invisible at frequencies below 10 GHz, could impact our knowledge of PS and, in particular, render the widely used radio-loudness parameter obsolete.

KEYWORDS

active galactic nuclei, peaked sources, narrow-line Seyfert 1, unified models

1 | INTRODUCTION

Peaked sources (PS) are a class of powerful ($\log P_{1.4\,\mathrm{GHz}} > 25$ W Hz^{-1}) radio sources characterized by a small linear size (<15 kpc) of their relativistic jets and by a peaked radio spectrum. The PS population is a mixed bag (O'Dea & Saikia 2021). Some may be variable radio sources with a temporarily inverted spectrum. Others may be transient sources in which the spectral shape remains the same over time. In this case, intermittent activity of the nucleus may turn the jet on and maintain it for 10^3–10^4 years, and then turn it off and remain quiescent for a longer interval (10^4–10^6 years, Czerny et al. 2009). Another option is the young age scenario, in which PS represents a population of young sources that are still developing and will eventually grow into classical radio galaxies (Fanti et al. 1995). Both of these scenarios have in common the young kinematical age of the relativistic jets.

However, PS is not the only class of sources, which may have kinematically young jets. Classified not based on their radio spectra as PS, but instead, on their optical spectra, narrow-line Seyfert 1 (NLS1) galaxies have by definition a full-width at half maximum of the Hβ emission line lower than 2,000 km s^{-1} (Osterbrock & Pogge 1985). Despite such narrow permitted lines, they are not obscured as Type 2 active galactic nuclei (AGN), but they are instead Type 1 AGN, in which the broad-line region (BLR) and the central engine are directly visible. Although alternative hypotheses exist (Decarli et al. 2008), the narrowness of permitted lines is typically attributed to low rotational velocity around a black hole with mass (10^6–10^8 $M_\odot$, Peterson & Wandel 1999) lower than that of other AGN. Since the bolometric luminosity of NLS1s is comparable to that of more massive AGN, they must be accreting close to the Eddington limit (e.g., see Foschini 2020; Gallo 2018; Komossa 2018; Lister 2018, for reviews on their properties).

These properties led to an interesting hypothesis. Let us consider two AGN, located at the same redshift, with the same physical structure and the same life cycle. If one of them has a lower black hole mass, it is reasonable to assume that its black hole has spent less time accreting efficiently in an active phase. In this sense, the low-mass AGN can be considered younger than the high-mass one. This could be the case for NLS1s, as they may be the progenitors of AGN with higher black hole masses (Mathur 2000), and more recent statistical analysis seems to confirm this scenario (Fraix-Burnet et al. 2017; Järvelä et al. 2017).

Some NLS1s harbor powerful relativistic jets that, when closely aligned with the line of sight (i.e., beamed), can be sources of γ-ray emission (Abdo et al. 2009). Such jetted NLS1s aligned with our line of sight seems to share most of the properties of their nonjetted counterparts, such as black hole mass and Eddington ratio (Berton et al. 2015), and for this reason, they could be the progenitors of other γ-ray sources like flat-spectrum radio quasars (FSRQ, Foschini et al. 2015). However, it is known that, when observed at large angles, FSRQs appear as high-excitation radio galaxies (HERGs, Giommi et al. 2012; Urry & Padovani 1995). We mentioned before that some PS sources could be young radio galaxies. Therefore, some of these genuinely young PS may be the misaligned counterpart (i.e., the parent population) of γ-ray NLS1s (Berton et al. 2017).

2 | A NEW UNIFIED MODEL?

The similarity between some PS and jetted NLS1s was already noticed 20 years ago, when the powerful radio source PKS 2004-447 was identified as a PS with an NLS1 optical spectrum (Oshlack et al. 2001). After that, a number of sources sharing both classifications have been found (Gu et al. 2015; Komossa et al. 2006; Liao & Gu 2020; Yao & Komossa 2021; Yuan et al. 2008). Based on this, Berton et al. (2016) proposed that a subclass of PS called low-luminosity compact (LLC) sources (Kunert-Bajraszewska et al. 2010) could be good candidates as part of the parent population of γ-ray NLS1s. Some of these LLCs can be optically classified as Type 2 HERGs (Kunert-Bajraszewska & Labiano 2010), and their black hole mass and Eddington ratio distributions overlap with those of beamed NLS1s. Berton et al. (2016) also studied their radio luminosity function (LF). This technique allows to add a model of relativistic beaming to the LF of an unbeamed population, which can be then compared to the observed LF of the beamed population (Padovani & Urry 1992). This analysis showed that LLC can belong to beamed NLS1s' parent population if the diffuse radio emission of the latter is negligible with respect to their nonthermal core emission. As later confirmed by Berton et al. (2018), this is exactly what is observed among beamed NLS1s that, unlike FSRQs (Antonucci & Barvainis 1988), typically lack diffuse emission.

A potential issue with this unification is that, while jetted NLS1s tend to be harbored in spiral galaxies (Berton et al. 2019; Hamilton et al. 2021; Järvelä et al. 2018; Kotilainen et al. 2016; Olguín-Iglesias et al. 2020), PS are usually hosted by ellipticals (O'Dea & Saikia 2021). However, in general, HERG-like PS tend to have bluer colors than LERG, possibly pointing toward a more gas-rich host (Heckman & Best 2014). Furthermore, to the best of our knowledge, no dedicated study has been carried out for LLC/HERGs. Since their central engine properties are similar to those of jetted NLS1s, it would not come as a surprise to find that they also are hosted by spirals. This point, anyway, clearly shows that jetted NLS1s cannot be unified with the whole population of PS. Only a very specific subset of them can be part of the parent population of jetted NLS1s, very likely those with a relatively low-mass black hole and a high Eddington ratio.

As previously mentioned, there is no doubt that NLS1s and some PS do share some properties. The two classifications are not mutually exclusive, since they are based on different frequencies. Several γ-NLS1s show peaks above 10 GHz, similarly to what is observed in some PS (Lähteenmäki et al. 2017). Furthermore, radio observations carried out with very long baseline interferometry (e.g., Caccianiga et al. 2017; Schulz et al. 2016) showed that some jetted NLS1s respect the criteria to be classified, in radio, as PS. Two of these jetted NLS1s with PS classification, PKS 2004–447 and 3C 286 (e.g., Berton et al. 2021; Yao & Komossa 2021), are also γ-ray sources included in the *Fermi* 4FGL. Since this catalog only includes six PS (Abdollahi et al. 2020), and two of them are NLS1s, it is clear that sources with both classifications are potentially very interesting candidates as high-energy emitters.

3 | THE RIDDLE OF INVISIBLE JETS

The most interesting discovery of the last decade in the NLS1 field (Foschini 2020) is the detection at 37 GHz of a few radio-quiet or even radio-silent (i.e. never detected in any radio survey) NLS1s with the Metsähovi Radio Telescope (Lähteenmäki et al. 2018). Seven of these objects were unexpectedly found flaring multiple times at Jy-level with relatively short timescales. The only reasonable mechanism to produce this kind of emission is by means of a relativistic jet, as seen in blazars. Follow-up observations with the Karl G. Jansky Very Large Array (VLA) revealed something even more unexpected. These NLS1s all have very faint emission at lower radio frequencies. Between 1.4 and 10 GHz, their flux densities are of the order of ~mJy or, more often, μJy (Berton et al. 2020). The beam sizes of VLA and Metsähovi are very different. This, however, cannot account for such a variable emission, as it would be located far from the nucleus or even outside of the host galaxy. Furthermore, new observations are revealing that radio flares correspond to a brightening of the nucleus at other frequencies (Romano et al., in prep). This indisputably proves that the flares are produced by the NLS1 nuclei. What can cause such a peculiar behavior?

The spectrum of these objects is dominated by a power-law with spectral index $\alpha_\nu \sim -0.7$ ($S_\nu \propto \nu^\alpha$) below 10 GHz. Above this frequency, instead, the spectrum is rising with a spectral index up to $\alpha_\nu = 6.8$. The emission at high frequency was measured only during a flaring state of the jet; therefore, this number is definitely an upper limit. However, it is evident that the spectrum cannot have the same spectral index measured at low frequencies up to ~37 GHz, or these flares would lead to an unrealistic increase in the flux density of >4,500 times.

An inverted radio spectrum is nothing new among PS, as it is known that small jets are peaking at relatively high frequencies. But in our case, the peak would be around 40 GHz, which would be unprecedented, and also short lived, because it would move too much lower frequencies in a few years. A more likely explanation for the inverted spectrum we observe is that the origin of the radio emission in the two frequency domains is different. At low frequency, the jet is not visible, and the radio emission is likely produced by a combination of nuclear activity and star formation (e.g., supernova remnants), which is often very strong in NLS1s (Sani et al. 2010). The high-frequency emission, instead, originates in a small-scale relativistic jet, possibly closely aligned with the line of sight as in blazars. We hypothesize that a dense region of ionized gas is present between the star-forming regions and the small-scale jet. The ionization source may be either young hot stars or a bow shock produced by the jet itself. The gas is optically thick at low frequencies because of free-free absorption. For this reason, only the emission from the star formation, which is occurring farther away, is visible at low frequencies. At high frequency, instead, the ionized gas is optically thin, and the jet radio emission can escape freely. The relativistic jet must have a relatively small scale, otherwise, the size and density of the region of ionized gas would be unrealistically large. This may be in agreement with the young age scenario for NLS1s. A small-scale jet, indeed, may have formed only rather recently.

4 | THE DEATH OF RADIO-LOUDNESS

The discovery of absorbed relativistic jets needs confirmation by means of multiwavelength observations. If our hypothesis is correct, however, it could have severe implications, especially regarding the use of the radio loudness parameter. Defined by Kellermann et al. (1989), it is the ratio between optical and radio flux densities, $R = S_{\mathrm{opt}}/S_{\mathrm{radio}}$. However, as suggested already in Padovani (2017) and Järvelä et al. (2017), AGN should be classified based on their real physical properties, not based on an artificial parameter with an arbitrary threshold. The radio loudness parameter had its use when our knowledge of AGN and different AGN-related phenomena was still limited, and most studies focused on either very bright and distant quasars, or nearby, only moderately luminous Seyferts. Due to this bias in interests, the so-called radio loudness dichotomy was formulated (Cirasuolo et al. 2003), stating that there are two intrinsically different populations of AGN: radio-loud and radio-quiet sources, and no smooth transition between the two populations. In this scheme, the high radio-loudness was associated with bright AGN with relativistic jets, and the radio-quiet sources were thought to be mostly nonjetted. During the past decades, it has become increasingly clear that the radio-loudness distribution of AGN is not bimodal (e.g., Järvelä et al. 2015), and this view of AGN is too simplistic.

Already 20 years ago Ho & Peng (2001) showed that when carefully measuring the radio-loudness of the nuclear component in radio-quiet Seyfert galaxies, majority of them would actually be classified as radio-loud. This highlights one of the issues with the radio-loudness parameter: the host galaxy. In nearby sources, the host galaxy can considerably contribute to the optical light measured from the galaxy, and decrease the radio-loudness of the source. This aspect is not taken into account in the original definition of the radio-loudness parameter. The host galaxy can also have an opposite effect, as shown in Caccianiga et al. (2015). They study a sample of radio-loud NLS1s and conclude based on their mid-infrared properties that actually some of these sources might appear radio-loud due to the enhanced star formation processes in the host galaxy.

The radio-loudness parameter is too ambiguous to be reliable, or even useful. In addition to the issues mentioned above, its value also depends on, for example, the optical and radio variability of AGN, the instruments used on either band, and their sensitivity. The final nail to the coffin of radio-loudness was the discovery of most likely relativistic jets in sources that were previously classified as radio-quiet or radio-*silent*. For now, these sources are a curiosity, but we do not know how common these or similar properties among AGN are. However, this example perfectly highlights the poor predicting power of the radio-loudness parameter, and it can be easily seen how using it might lead to misleading or even wrong results, especially among sources, such as NLS1s, where different components can co-exist. Using such a parameter to, for example, divide samples in statistical studies would obviously skew the results, and lessen their reliability and significance. These problems can be avoided by properly classifying the sources based on their physical properties, instead of a vague parameter, repeatedly proven to be misleading. The radio-loudness parameter truly seems to be a relic of the past, and we thus kindly suggest that we finally lay it to rest.

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