Publication Year	2017
Acceptance in OA@INAF	2020-08-27T14:35:15Z
Title	What we talk about when we talk about blazars?
Authors	FOSCHINI, LUIGI
DOI	10.3389/fspas.2017.00006
Handle	http://hdl.handle.net/20.500.12386/26898
Journal	FRONTIERS IN ASTRONOMY AND SPACE SCIENCES
Number	4

frontiers
in Astronomy and Space Sciences

MINI REVIEW
published: 11 July 2017
doi: 10.3389/fspas.2017.00006

What We Talk about When We Talk about Blazars?

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After the discovery of powerful relativistic jets from Narrow-Line Seyfert 1 Galaxies, and the understanding of their similarity with those of blazars, a problem of terminology was born. The word blazar is today associated to BL Lac Objects and Flat-Spectrum Radio Quasars, which are somehow different from Narrow-Line Seyfert 1 Galaxies. Using the same word for all the three classes of AGN could drive either toward some misunderstanding, or to the oversight of some important characteristics. I review the main characteristics of these sources, and finally I propose a new scheme of classification.

Keywords: relativistic jet, blazar, quasar, BL Lac Object, Narrow-Line Seyfert 1 galaxy, black hole, neutron star

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Specialty section:
This article was submitted to Milky Way and Galaxies, a section of the journal Frontiers in Astronomy and Space Sciences

Received: *29 May 2017*
Accepted: *23 June 2017*
Published: *11 July 2017*

Citation:
Foschini L (2017) What We Talk about When We Talk about Blazars? Front. Astron. Space Sci. 4:6. doi: 10.3389/fspas.2017.00006

1. INTRODUCTION

The title is borrowed from Haruki Murakami's *What we talk about when we talk about running*, who, in turn, borrowed it from Raymond Carver's *What we talk about when we talk about love*. Far from competing with those two outstanding authors, I just would like to draw the attention on some recent discoveries about relativistic jets, and how to include them into the unified model of active galactic nuclei (AGN) with jets. I would like to underline that this is not a challenge to the unified model, but rather the request of an evolution and an improvement.

It is not the first time that there is an evolution in the terminology of this type of cosmic sources. This should not be looked as a mere fashion about words. It is true that physical objects exist independently on how we name them, but it is also true that using the most proper words makes it easier to study them, by avoiding to remain stuck on a swamp of fake problems and misleading questions. When Gregorio Ricci Curbastro and Tullio Levi-Civita proposed the tensor calculus, many other mathematicians rejected it, because they thought it was just a mere rehash of old maths. When speaking about Ricci Curbastro, Luigi Bianchi told that he preferred to find new things with old methods, rather than to find old things with new methods (cited in Toscano, 2004). On the opposite, Henri Poincaré wrote that a proper notation in mathematics has the same importance of a good classification in natural science, because it allows us to connect each other many events without any apparent link (cited in Bottazzini, 1990).

Back to the topic of this essay, I would like to remind some past changes in terminology about relativistic jets. In 1978, Ed Spiegel proposed the term *blazar* as a contraction of the words BL Lac Objects and Optically Violently Variable Quasars (OVV) (Angel and Stockman, 1980); in 1994–1995, Paolo Padovani and Paolo Giommi proposed to rename radio-selected BL Lac Objects (RBL) as low-energy cutoff BL Lacs (LBL), and X-ray selected BL Lac Objects (XBL) changed to high-energy cutoff BL Lacs (HBL) (Giommi and Padovani, 1994; Padovani and Giommi, 1995); also the Fanaroff-Riley classes of radio galaxies changed to low- and high-excitation radio galaxies (LErG, HErG) (Hine and Longair, 1979; Laing et al., 1994; Buttiglione et al., 2010). In his opening talk at the conference *Quasar at all cosmic epochs* (Padova, April 2–7, 2017), Paolo Padovani proposed to stop using radio loud/quiet terms and to start speaking about jetted AGN or not. I was less severe in my thoughts on radio loudness some years ago (Foschini, 2011), although I agreed with Padovani. It is time to be resolute in changing terminology. Also Martin Gaskell wrote: "I tell students that classification is one of the first step in science. As science progresses, however, I believe that we need to move toward physically meaningful classification schemes as soon as possible. To achieve this, we need to be willing to modify our definitions, or else we can impede progress" (cited in D'Onofrio et al., 2012). This means to move from a purely observational classification to a terminology with more physical grounds. It should be needless to say, but before establishing the type of a cosmic source, it is necessary to study it. A simple measure is the easy way, but it is also the most prone to errors.

Today, AGN with jets are unified according to the scheme by Urry and Padovani (1995, Table 1), which in turn summarizes many years of contributions from pioneers (see the historical review in D'Onofrio et al., 2012). Urry and Padovani's scheme has its pillars in three main factors: viewing angle, optical spectrum, radio emission. They also suggested a fourth factor, the black hole spin, which should be greater for jetted AGN.

With reference to jetted AGN only, the Urry and Padovani's unified model can be divided into two main classes and four subclasses on the basis of viewing angle and optical spectrum (Urry and Padovani, 1995):

1. Blazar (small viewing angle, beamed sources):
   (a) Flat-spectrum radio quasar (FSRQ), prominent emission lines in the optical spectrum;
   (b) BL Lac Object, weak emission lines or featureless continuum in the optical spectrum;
2. Radio galaxies (large viewing angles, unbeamed sources):
   (a) HErG, prominent emission lines in the optical spectrum;
   (b) LErG, weak emission lines or featureless continuum in the optical spectrum;

The mass of the central spacetime singularity was generally in the range $\sim 10^{8-10}M_{\odot}$ (Buttiglione et al., 2010; Ghisellini et al., 2010; Tadhunter, 2016), which seemed to fit well with the elliptical galaxies hosting this type of cosmic sources (Olguín-Iglesias et al., 2016). The limited range meant to neglect the mass when scaling the jet power. Therefore, the main factor regulating the electromagnetic emission became the electron cooling, which is the basis of the so-called *blazar sequence* (Fossati et al., 1998; Ghisellini et al., 1998). The observed blazar sequence indicated that the spectral energy distribution (SED) of high-power blazar (FSRQs) had the synchrotron and the inverse-Compton peaks at infrared and MeV-GeV energies, respectively, while that of low-power sources (BL Lac Objects) had the peaks shifted to greater energies (UV/X-rays and TeV, respectively) (Fossati et al., 1998). This was explained as different cooling of relativistic electrons due to different environment, rich of photons or not (physical blazar sequence, Ghisellini et al., 1998). In addition, since no other jetted AGN with smaller masses were known, it was thought that the generation of a relativistic jet required a minimum black hole mass (Laor, 2000; Chiaberge and Marconi, 2011).

Truly speaking, the lack of small-mass jetted AGN was a selection bias. For example, in Miley and Miller (1979) studied a sample of 34 quasars with $z < 0.7$: their sample included also objects with small black hole mass, which resulted to have compact radio morphology. In Wills and Browne (1986) studied a sample of 79 quasars with the same redshift range, but selecting only bright sources (mag < 17): small-mass objects disappeared. Therefore, jets from small-mass AGN were known at least since seventies, but they were disregarded, likely because of the poor instruments sensitivity. The recent technological improvements resulted in an increase of the cases of powerful jets hosted in spiral galaxies (hence, small mass of the central black hole) (Keel et al., 2006; Morganti et al., 2011). Also recent surveys showed that disk/spiral hosts are not just an exception, but they could be a significant fraction of jetted AGN (Inskip et al., 2010; Coziol et al., 2017). Particularly, Coziol et al. (2017) confirmed the results of Miley and Miller (1979): small-mass compact objects have generally weak, and compact radio jets.

2. HIGH-ENERGY GAMMA RAYS FROM NARROW-LINE SEYFERT 1 GALAXIES

The turning point occurred in 2009, with the detection of high-energy γ rays from Narrow-Line Seyfert 1 Galaxies (NLS1), thus providing evidence of powerful relativistic jets from small-mass AGN (Abdo et al., 2009a,b,c; Foschini et al., 2010) (see also Foschini, 2012b for a historical review). NLS1s do have small-mass central black holes ($\lesssim 10^8 M_{\odot}$), high accretion luminosity (close to the Eddington limit), prominent optical emission lines, but relatively weak jet power, comparable to BL Lac Objects (Foschini et al., 2015). Kinematics of radio components revealed superluminal motion ($\sim$10c Lister et al., 2016; see also Angelakis et al., 2015; Lähteenmäki et al., 2017 for more information about radio properties), while infrared colors indicated an enhanced star formation activity (Caccianiga et al., 2015). The host galaxy is not yet clearly defined: there is evidence that NLS1 without jets are hosted by spiral galaxies, but $\gamma-$ray NLS1 are still poorly known. However, early observations of a handful of sources point to disk galaxy hosts[1], the result of either a recent merger or a secular accretion (Zhou et al., 2007; Antón et al., 2008; Hamilton and Foschini, 2012; León Tavares et al., 2014; Kotilainen et al., 2016; Olguín-Iglesias et al., 2017).

All the observed characteristics of NLS1s suggested that this class of AGN could be the low-mass tail of the quasars distribution (Abdo et al., 2009a; Foschini et al., 2015). Indeed, as proved by Berton et al. (2016), the NLS1s luminosity function matches that of FSRQs. The parent population of jetted NLS1s could be that of Compact Steep Spectrum (CSS) HErG (Berton et al., 2016, in press). This fits well with the idea that NLS1s are quasars at the early stage of their evolution or rejuvenated by a recent merger (Mathur, 2000).

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[1] Two opposite interpretation were proposed for FBQS J1644+2619, a spiral barred host (Olguín-Iglesias et al., 2017), and an elliptical galaxy (D'Ammando et al., 2017). However, the former observation seems to be more reliable, because done with a much better seeing than the latter.

However, I would like to underline that it is not a matter of NLS1s only, but of small-mass AGN. Recent surveys with *Fermi/LAT* (Shaw et al., 2012; Foschini et al., 2016) and the *Sloan Digital Sky Survey* (Best and Heckman, 2012) indicated that jetted AGN with small-mass black holes are not restricted to NLS1s-type AGN. The exact observational classification is not the point, but what is important is the relatively small mass of the central spacetime singularity. This confirms once again that the mass threshold to generate the relativistic jet in AGN was just an observational bias.

3. THE UNIFICATION OF RELATIVISTIC JETS

Removing the mass-threshold bias has the important consequence of the unification of relativistic jets from AGN and from Galactic X-ray binaries (XRBs) (Foschini, 2012a, 2014). In a jet power vs. disk luminosity graph (see Figure 7.4 of Foschini, 2017), NLS1s populate the previously missing branch of small-mass highly-accreting compact objects, the analogous of accreting neutron stars for the XRBs sample (see also Paliya et al., 2016 for a larger sample of AGN). By applying the scaling relationships elaborated by Heinz and Sunyaev (2003), it is possible to merge the AGN and XRBs populations. A residual dispersion of about three orders of magnitudes remain (see Foschini, 2012a, 2014): measurements errors could account for about one order of magnitude, while the remaining two could likely to be due to the spin of the compact object (Heinz and Sunyaev, 2003; Mościbrodzka et al., 2016), whose measure is still missing or largely unreliable (see also Foschini, 2017).

4. IMPLICATIONS OF THE UNIFICATION

Having proved the Heinz and Sunyaev's scaling theory (Heinz and Sunyaev, 2003), the jet power vs. disk luminosity graph could be used also to understand and to visualize some implications of the unification of relativistic jets (**Figure 1**). Each population has two branches, depending on the main factor driving the changes in the jet power. The dashed blue rectangle in **Figure 1A** summarizes the blazar sequence (Fossati et al., 1998; Ghisellini et al., 1998): the black hole masses of blazars are within about one, maximum two, orders of magnitudes, and, therefore, the main changes in the jet power are driven by the electron cooling in different environments. The red rectangle in **Figure 1A** refers to similar environments (FSRQs and NLS1s), but largely different masses ($\gtrsim 10^8 M_\odot$ vs. $\lesssim 10^8 M_\odot$, respectively), which in turn implies that the main change in the jet power is due to the mass of the central black hole (Heinz and Sunyaev, 2003). The relatively small-mass black hole ($\lesssim 10^8 M_\odot$) is necessary to explain the weak jet power of NLS1s, which is comparable with BL Lac Objects (Foschini et al., 2015): as the environment of NLS1s is rich of photons like FSRQs, a large black hole mass would mean that relativistic electrons of the jet do no cool efficiently with so many photons, thus contradicting a basic physical law. Indeed, BL Lac Objects have weak jet and large masses ($\gtrsim 10^8 M_\odot$), but their environment is photon-starving (see also Foschini, 2017). The NLS1s branch (red rectangle) also prove that the observational blazar sequence (the dashed blue rectangle only Fossati et al., 1998) was due to a bright-source selection bias, although the physical blazar sequence (Ghisellini et al., 1998) remains valid, as it simply refers to how relativistic electrons cool depending on photon availability.

When comparing the AGN with XRBs samples, one can note that the blazar sequence corresponds somehow to the stellar-mass black hole states, but on different time scales. Galactic black holes evolve on human time scales: it is possible to observe a state change of a black hole along months/years of observations. A quasar requires some billion of years to swallow most of the available interstellar gas and to become a BL Lac Object (Böttcher and Dermer, 2002; Cavaliere and D'Elia, 2002; Maraschi and Tavecchio, 2003). This opens another implication, namely the cosmological evolution (**Figure 1B**). The blazar evolutionary sequence (Cavaliere and D'Elia, 2002; Böttcher and Dermer, 2002; Maraschi and Tavecchio, 2003) suggested that quasar are young AGN, which become BL Lac Objects as they grow. This scenario has to be updated now by adding also NLS1s, which are thought to be a low-redshift analogous of the early quasars (Mathur, 2000; Berton et al., in press). Therefore, one could think at the sequence NLS1s → FSRQs → BL Lac Objects, going from small-mass highly-accreting to large-mass poorly-accreting black holes, as different stages of the cosmological evolution of the same type of source (young → adult → old, **Figure 1B**). This view implies that BL Lac Objects have the largest masses, being (perhaps) the final stage of the cosmic lifetime, at odds with the results of some surveys (Ghisellini et al., 2010). Again, if one removes the bright sources selection bias, it is possible to find that indeed BL Lacs/LErGs do have masses larger than FSRQs/HErGs (Best and Heckman, 2012).

On the other side of the evolution, it is worth noting the presence of strong star formation in NLS1s, with infrared properties similar to UltraLuminous InfraRed Galaxies (ULIRGs) (Caccianiga et al., 2015). This points also to some link to the very birth of a quasar and its jet, which in turn could be an essential angular momentum relief valve to enhance the accretion (Jolley and Kuncic, 2008). ULIRGs as early quasar stage were already studied by Sanders et al. (1988a,b) and it is interesting to note the presence in his sample of both the NLS1 and the quasar prototypes (I Zw 1, and 3C 273, respectively).

It is also worth noting the application of the same sequence to the XRBs population, which implies a transition from accreting neutron stars to stellar-mass black holes (Belczynski et al., 2012; Zdziarski et al., 2013; Neustroev et al., 2014).

5. CONCLUSION: A RENEWED UNIFIED SCHEME

The Urry and Padovani's scheme (Urry and Padovani, 1995) updated with the addition of NLS1s and their parent population of CSS/HErG is shown in **Figure 2A**. However, this generates

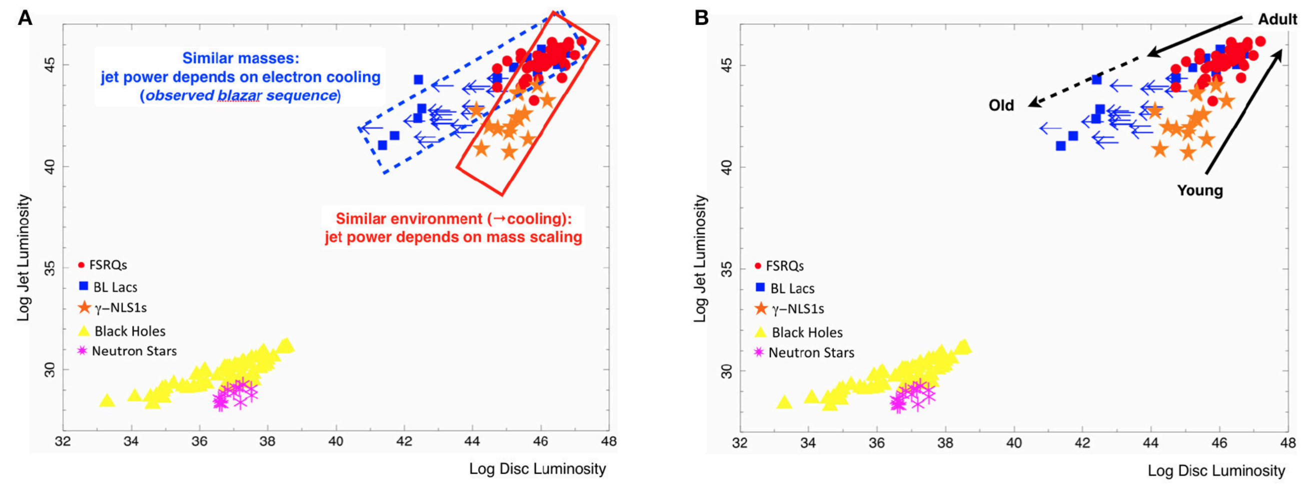
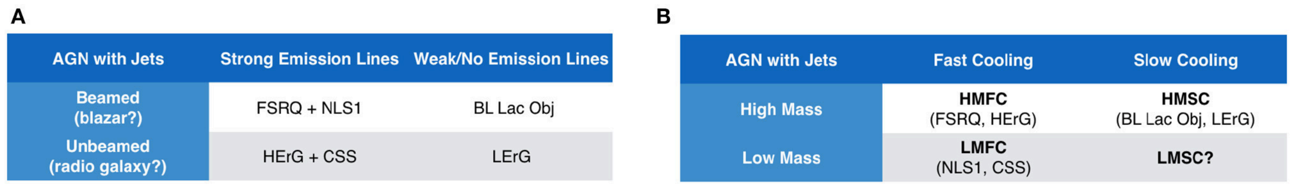


FIGURE 1 | Implications of the unification of relativistic jets. The AGN sample includes FSRQs (red circles), BL Lac Objects (blue squares or arrows for upper limits in disk luminosity), and NLS1s (orange stars). The XRB sample includes different states of some stellar-mass black holes (yellow triangles) and accreting neutron stars (magenta asterisks). HLX-1 is the only known jetted ultraluminous X-ray source with a reliable intermediate-mass black hole. See Foschini (2014) and references therein for details. **(A)** Different branches, different mechanisms. **(B)** Cosmological evolution.



A

AGN with Jets	Strong Emission Lines	Weak/No Emission Lines
Beamed (blazar?)	FSRQ + NLS1	BL Lac Obj
Unbeamed (radio galaxy?)	HErG + CSS	LErG

B

AGN with Jets	Fast Cooling	Slow Cooling
High Mass	**HMFC** (FSRQ, HErG)	**HMSC** (BL Lac Obj, LErG)
Low Mass	**LMFC** (NLS1, CSS)	**LMSC?**

FIGURE 2 | Changing terms in the unification scheme. **(A)** The updated Urry and Padovani's scheme. **(B)** Physical unification scheme.

some problem in terminology. The words blazar and radio galaxy indicate a certain type of cosmic source characterized by a high black hole mass and hosted by an elliptical galaxy. The easy addition of NLS1s and CSS to the above scheme risks to hide important information, as outlined in the previous section (different black hole mass, different host, ...). This is not a negligible detail: remind the misleading research directions caused by the bright sources selection bias, such as the threshold in the jet generation and the observed blazar sequence. Martin Gaskell wrote: "When you attach different classification to things, it is all too easy to get convinced that they are different things." (cited in D'Onofrio et al., 2012). On the opposite, if you attach the same name to different things, it is all too easy to get convinced that they are the same thing. Therefore, on one side, we need to unify jetted AGN, but, on the other side, we need to keep some information about the roots of this unification to understand the physical processes driving the observational characteristics. The jets of AGN and XRBs are similar, but their power depends on the mass of the compact object, its spin, and its accretion (environment). It is important to note that **Figures 1A,B** were built by using the jet power corrected for beaming. Indeed, it places on the same plane both beamed AGN and XRBs, which are not so beamed, as it is quite difficult for a Galactic jet to point toward the Earth, being both on the same equatorial Galactic plane[2]. The addition of HErG/LErG/CSS sources would not change the two-branches structure for each population. Therefore, it should be possible to drop also the distinction beamed/unbeamed. From a physical point of view, the two most important factors in scaling the jet power are the mass of the compact object and the nearby environment (for the electron cooling), which in turn depends on the accretion. As already stated, the spin determines a larger dispersion only (Heinz and Sunyaev, 2003; Mościbrodzka et al., 2016). Therefore, a more physical-based unification could be set up by dividing the sources depending on the mass and on the cooling only (**Figure 2B**). The dividing mass is $\sim 10^8 M_\odot$ not because of historical reasons, but because no BL Lac Object with small mass is known. Indeed, I have left a question mark on the LMSC (Low Mass Slow Cooling) cell. Current BL Lacs should be the latest stage of the cosmological evolution of jetted AGN, and, therefore, a small-mass BL Lac would mean that there was no evolution. Did such AGN have no matter enough for accretion? As there are other small-mass AGN, which are not necessarily NLS1-type (Best and Heckman, 2012; Shaw et al., 2012; Foschini et al., 2016), it would be interesting to understand if some of them have

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[2] Galactic compact objects with jets are named microquasars, but there is no such thing as a microblazar, i.e., a Galactic jet pointed toward the Earth.

a photon-starving environment. Perhaps, one intriguing case could be PKS 2004−447 ($z = 0.24$) that showed observational characteristics somehow different from the other jetted NLS1s (Abdo et al., 2009c; Kreikenbohm et al., 2016; Schulz et al., 2016). There was also some disagreement on its classification as NLS1s, on the basis of the weakness of the FeII multiplets (Gallo et al., 2006; Komossa et al., 2006). It is interesting to point out that it is the only NLS1 (orange star) in the region of BL Lac Objects (blue squares or arrows) in **Figures 1A,B**.

The same terminology adapts well also to the XRB population: in this case, the dividing mass should be $\sim 3M_{\odot}$, which is the minimum for a Galactic black hole. Also in this case, the LMSC cell remains with a question mark, but the question is more intriguing, because of shorter time scales. Could it be filled by pulsars? Similar questions on AGN evolution apply here.

As a final remark I think it is important to stress the different view offered by a terminology change built on more physical ground, rather than to focus on observational details.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

FUNDING

This work has been partially supported by PRIN INAF 2014 “Jet and astro-particle physics of gamma-ray blazars” (PI F. Tavecchio).

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Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer DB and handling Editor declared their shared affiliation, and the handling Editor states that the process nevertheless met the standards of a fair and objective review.