Looking below the floor: constraints on the AGN radio luminosity functions at low power.

Alessandro Capetti$^1$ and Claudia M. Raiteri$^1$

$^1$INAF-Osservatorio Astrofisico di Torino, via Osservatorio 20, 10025 Pino Torinese, Italy

ABSTRACT

We constrain the behavior of the radio luminosity function (RLF) of two classes of active galactic nuclei (AGN) namely AGN of low radio power (LRP) and BL Lac objects. The extrapolation of the observed steep RLFs to low power predicts a space density of such objects that exceeds that of the sources that can harbor them and this requires a break to a shallower slope. For LRP AGN we obtain $P_{\text{br,LRP}} \gtrsim 10^{20.5} \text{ W Hz}^{-1}$ at 1.4 GHz to limit their density to be smaller than that of elliptical galaxies with black hole masses $M_{\text{BH}} > 10^{7.5} M_\odot$. By combining this value with the limit derived by the observations the break must occur at $P_{\text{br,LRP}} \sim 10^{20.5} - 10^{21.5} \text{ W Hz}^{-1}$. For BL Lacs we find $P_{\text{br,BLLAC}} \gtrsim 10^{23.3} \text{ W Hz}^{-1}$ otherwise they would outnumbe the density of weak-lined and compact radio sources, while the observations indicate $P_{\text{br,BLLAC}} \lesssim 10^{24.5} \text{ W Hz}^{-1}$. In the framework of the AGN unified model a low luminosity break in the RLF of LRP AGN must correspond to a break in the RLF of BL Lacs. The ratio between $P_{\text{br,LRP}}$ and $P_{\text{br,BLLAC}}$ is $\sim 10^3$, as expected for a jet Doppler factor of $\sim 10$.

Key words: galaxies: active – galaxies: BL Lacertae objects: general – galaxies: jets

1 INTRODUCTION

Many astrophysical quantities obey a distribution well described by power-laws. Important insights into the physical processes producing such distributions can be obtained from their power-law index. In addition, the location at which the distribution departs from a power-law is also of great importance. In most cases, a change in the distribution laws is reflected in the peak frequency in the synchrotron emission of active galactic nuclei (AGN) namely AGN of low radio power (LRP) and BL Lac objects. Therefore, the determination of the behavior of the distributions at the low end as it might reveal the presence of, e.g., a minimum mass for the formation of a star or a galaxy. Unfortunately, the low end behavior is often inaccessible to observations or, in other cases, it is blurred by the emergence of strong selection biases.

In this Letter we focus on the radio luminosity function (RLF) of two classes of active galaxies at low redshift, $z < 0.1$. The first is formed by low radio power (LRP) AGN; within the considered redshift limit, most of the radio emitting AGN are indeed objects of low power, $\log(P_r/\text{ W Hz}^{-1}) \lesssim 24$. The second consists of BL Lac objects. According to the unified model for AGN, these two RLFs are expected to be connected with each other, as LRP AGN should represent the parent population of BL Lac objects. In both cases the RLFs are observationally well defined over a very broad range of radio power. The RLF of LRP AGN also presents a break at high luminosity. Conversely, at their low luminosity end, both RLFs are well described by a pure power law by current observations, without clear signs of a change in their slopes. In this Letter we show that it is nonetheless possible to constrain the power at which a low luminosity break in the RLF must occur.

Throughout the paper we adopt $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.30$, and $\Omega_{\Lambda} = 0.7$.

2 THE RADIO AGN LUMINOSITY FUNCTION

The number density of AGN cannot exceed that of their potential hosts: this argument has been used by Mauch & Sadler (2007) and Cattaneo & Best (2009) to constrain the low luminosity behavior of their RLF. They found that a break must occur at a radio luminosity $\log(P_r/\text{ W Hz}^{-1}) \sim 19.5$ and 19.2, respectively. We use the same rationale, but including the information that their hosts, as shown in more detail below, are associated almost exclusively to very large black holes.

The RLF of nearby galaxies extending to the lowest
luminosity has been obtained by Mauch & Sadler (2007). It is derived from a sample of 7824 radio sources from the 1.4 GHz NVSS survey cross-correlated with the second data release of the 6 degree Field Galaxy Survey (6dFGS, Jones et al. 2005). Mauch & Sadler separated radio sources associated to AGN from star-forming galaxies relying on their optical spectra. Their resulting RLF covers the range \( \log(P_r/\text{W Hz}^{-1}) = 20.4 - 26.4 \) and shows a steepening at high luminosities (above \( \log(P_r/\text{W Hz}^{-1}) = 24.59 \)).

Best & Heckman (2012) obtained an independent estimate of the AGN RLF. This is slightly shallower (reaching a luminosity \( \log(P_r/\text{W Hz}^{-1}) \sim 22 \)) but, since their sample is drawn from the SDSS, they could take advantage of the optical data to better characterize their properties. The main result is that their hosts are almost exclusively massive early-type galaxies with black hole masses (derived from the stellar velocity dispersion adopting the Tremaine et al. 2002 law) larger than \( \log(M_{BH}/M_\odot) \sim 7.8 \) (see also Baldi & Capetti 2010).

The SDSS survey provides us with a highly complete sample that can be used to estimate the number density of galaxies with large black holes. To this purpose, we analyze the 818,333 galaxies (MPA-JHU sample hereafter) in the value-added spectroscopic cat- log produced by the Max Planck Institute for Astrophysics, and the Johns Hopkins University, and available at [http://www.mpa-garching.mpg.de/SDSS/](http://www.mpa-garching.mpg.de/SDSS/) (Brinchmann et al. 2004; Tremonti et al. 2004). We consider all galaxies from redshift \( z = 0.05 \) to \( z = 0.1 \) to ensure a high level of completeness (see below) within the largest possible volume, which results in 0.053 Gpc\(^3\).

We then select elliptical galaxies in the MPA-JHU sample by setting a threshold to the concentration index \( C_r \geq 2.6 \) (e.g. Strateva et al. 2001; Kauffmann et al. 2003; Bell et al. 2003) and to their stellar velocity dispersion adopting, conservatively, \( \sigma_{\text{stellar}} \geq 400 \text{ km s}^{-1} \), corresponding to \( \log(M_{BH}/M_\odot) \geq 7.5 \), finding \( \sim 38,000 \) objects. The resulting sample has a high level of completeness. According to Montero-Dorta & Prada (2009) the completeness of the SDSS decreases with decreasing apparent magnitude, starting at \( \sim 95\% \) at the SDSS spectroscopic limit of \( r = 17.77 \), and being still higher than \( 80\% \) at \( r = 13.25 \). The vast majority of the LRP AGN hosts have a magnitude in the range \( -23.5 < M_K < -26.5 \) (Mauch & Sadler 2007). This translates into \( r = 13.3 - 16.3 \) at \( z = 0.05 \) (and \( r = 14.8 - 17.8 \) at \( z = 0.1 \) having adopted \( r - K = 3.0 \) (Chang et al. 2006). This implies that most of such galaxies in the selected redshift range are included in the MPA-JHU catalog.

We now estimate how the total number of predicted LRP AGN grows rapidly at decreasing \( P_{br,\text{LRP}} \) (Fig. 1 right panel). For \( m = 0 \) it exceeds the total number of available hosts when \( \log(P_{br,\text{LRP}}/\text{W Hz}^{-1}) \sim 21.8 \), a value that is inconsistent with the Mauch & Sadler results even assuming that all massive galaxies host a LRP AGN.

We conclude that: 1) the RLF of LRP AGN must break to a shallower slope for radio luminosities smaller than \( \log(P_r/\text{W Hz}^{-1}) \sim 20.5 - 21.5 \), and 2) the number density below \( P_{br,\text{LRP}} \) must significantly decrease, leading to a peak in its distribution.

### 3 THE BL LAC OBJECTS LUMINOSITY FUNCTION

In this section we consider the RLF of BL Lacs at 1.4 GHz. We adopt the same line of reasoning followed above. In this case, the constraint on the RLF is derived imposing the requirement that the total number of BL Lacs does not exceed the total number of appropriate (see below) radio sources in the same volume.

Best & Heckman (2012) provides us with a sample of 18,286 AGN obtained by combining the SDSS DR7 MPA-JHU sample with the NVSS and the FIRST surveys, down to a flux density level of 5 mJy in the NVSS. We consider the same volume as in Sect. 2, i.e., \( 0.05 \leq z \leq 0.1 \). We select the sources with 1) a rest-frame equivalent width of all emission lines derived above should be con-

| number density of galaxies with large black holes. To this purpose, we analyze the 818,333 galaxies (MPA-JHU sample hereafter) in the value-added spectroscopic cat- log produced by the Max Planck Institute for Astrophysics, and the Johns Hopkins University, and available at [http://www.mpa-garching.mpg.de/SDSS/](http://www.mpa-garching.mpg.de/SDSS/) (Brinchmann et al. 2004; Tremonti et al. 2004). We consider all galaxies from redshift \( z = 0.05 \) to \( z = 0.1 \) to ensure a high level of completeness (see below) within the largest possible volume, which results in 0.053 Gpc\(^3\).

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We now estimate how the total number of predicted LRP AGN varies depending on the behavior of the RLF at low power. A low luminosity break must occur in order to avoid the divergence of the LRP AGN number. The Mauch & Sadler results suggest that it is located below \( \log(P_r/\text{W Hz}^{-1}) \sim 21.6 \), where the limited number of observed objects makes the RLF shape uncertain. We assume that the LRP AGN number density follows, below a break luminosity \( P_{br,\text{LRP}} \), a power law with an index \( m \). We investigate the effects of varying \( m \) from 0 (a flat number count distribution) to infinity (equivalent to a sharp cutoff below \( P_{br,\text{LRP}} \)), see the left panel of Fig. 1. We integrate numerically the RLF starting from \( \log(P_r/\text{W Hz}^{-1}) \sim 18.4 \), a factor of 100 below the observational limit: the total number of predicted LRP AGN grows rapidly at decreasing \( P_{br,\text{LRP}} \) (Fig. 1 right panel). For \( m = 0 \) it exceeds the total number of available hosts when \( \log(P_{br,\text{LRP}}/\text{W Hz}^{-1}) \sim 21.8 \), a value that is inconsistent with the Mauch & Sadler results even assuming that all massive galaxies host a LRP AGN.

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in the MPA-JHU galaxies catalog). However, this possibility can be discarded. First of all, in the Roma-BZCAT catalog of BL Lacs (Massaro et al. 2009) there are only 8 objects with 0.05 \( \leq z \leq 0.1 \) and covered by the DR7. All of them have been selected as SDSS spectroscopic targets. Furthermore, the brightest of these objects has a radio luminosity of \( 1.3 \times 10^{24} \) W Hz\(^{-1} \). We estimated the corresponding non-thermal contribution to the optical (\( r \) band) magnitude for similarly bright objects by assuming, conservatively, a radio-to-optical spectral index of 0.5, typical of high energy peaked BL Lacs (Padovani et al. 2007). We obtain \( r = 17.5 \) at \( z = 0.05 \) (and \( r = 19.0 \) at \( z = 0.1 \)), \( \sim 1\)–4 magnitudes fainter than LRP AGN hosts. Only much brighter BL Lacs might be confused with stars. However, very luminous sources have a low space density and indeed no such object, that would have been easily discovered, is known within the volume considered.

We conclude that our estimate of 267 objects is a robust upper limit to the BL Lacs number in our volume.

Padovani et al. (2007) derived the RLF of BL Lacs at 5 GHz based on the Deep X-ray Radio Blazar Survey. They obtained a RLF consistent with a single power-law with a slope of \( 2.12 \pm 0.16 \) in the range \( \log (P_r / \text{W Hz}^{-1}) \sim 23.8-26.8 \). By adopting this RLF we estimate the predicted number of BL Lacs in the selected volume when varying the luminosity, \( P_{br,BLLAC} \), at which the RLF breaks, see Fig. 2. In our calculation we assume a null radio spectral index \( \alpha = 0 \) to convert from 5 to 1.4 GHz and take into account that objects with radio flux density smaller than 5 mJy are not included in our sample (this effect causes the flattening of \( \log N \) for \( \log (P_{br,BLLAC}/\text{W Hz}^{-1}) \leq 23 \) in Fig. 2). We conclude that the number of BL Lacs predicted by extrapolating their RLF to low luminosities exceeds the total number of possible hosts for \( \log (P_{br,BLLAC}/\text{W Hz}^{-1}) \leq 23.3-23.5 \), depending on the RLF slope below the break. On the other hand, the RLF data points of Padovani et al. exclude \( \log (P_{br,BLLAC}/\text{W Hz}^{-1}) \geq 24.5 \).

We conclude that the RLF of BL Lacs must break to a shallower slope for radio luminosities smaller than \( \log (P_r / \text{W Hz}^{-1}) \sim 23.3-24.5 \).
4 DISCUSSION AND CONCLUSIONS

The results presented indicate that the RLFs at 1.4 GHz of both LRP AGN and BL Lacs must decrease their slope at, or just above, the low luminosity limit at which they are currently determined. This might appear as a contrived coincidence, while, conversely, it is the natural consequence of the behavior of the RLF at low power. In fact, the number of objects below the break that can be detected in a flux limited survey depends on the radio power as $P_{\text{lum}}^{3/2 - m}$, where $m$ is the number density slope for $P_{\text{lum}} < P_{\text{br}}$. The strong dependence on $P_{\text{br}}$ implies that these objects are missing altogether in the currently available surveys (or at most found in a small number) and this prevents the RLF determination below $P_{\text{br}}$.

For LRP AGN we find that the number density below the break must significantly decrease producing a peak in the distribution. It is tempting to associate the presence of this peak to a minimal level of accretion at which a radio jet can be produced. A better definition of the RLF at low luminosity is essential in this context: in the first case, we expect to find that all potential hosts harbor a LRP AGN, albeit of very low luminosity while, in the second alternative, the occupation fraction would never reach 100%. Note that [Kimball et al. (2011)] found a similar dramatic fall of the number density from the analysis of a sample of 179 QSOs $(M_0 < 23)$ from the SDSS in the redshift range $0.2 < z < 0.3$, for radio luminosities below $\log (P_{\text{br}}/\text{W Hz}^{-1}) \sim 21$ (at 6 GHz).

Unfortunately, we have only sparse information on the radio properties of massive galaxies below $\log (P_{\text{br}}/\text{W Hz}^{-1}) \sim 20$. These can be obtained with deep targeted observations of nearby galaxies. In the Virgo clusters there are two (out of 11) giant elliptical galaxies lacking of any sign of radio emission down to a limit of clusters there are two (out of 11) giant elliptical galaxies deep targeted observations of nearby galaxies. In the Virgo cluster there are two (out of 11) giant elliptical galaxies lacking of any sign of radio emission down to a limit of $\log (P_{\text{br}}/\text{W Hz}^{-1}) \sim 18.6$ (Capetti et al. 2009), despite their large mass ($M_0 \sim 10^{11.5} M_\odot$) and large black hole mass ($M_{\text{BH}} \sim 10^8 - 10^{9.5} M_\odot$). The small number statistics prevent us to derive any firm conclusion based on these observations, but they apparently favor the interpretation that not all massive galaxies are able to produce a radio jet.

The two RLFs considered in this Letter are expected to be linked with each other. Indeed, according to the AGN unified scheme, BL Lacs are the beamed version of low luminosity AGN (see e.g., Urry & Padovani 1995; Tadhunter 2008), i.e., BL Lacs are objects in which a highly relativistic jet is seen at an angle close to our line of sight. This accounts for their extreme properties, such as strong flux variability and apparent superluminal motion of radio components. The effects of relativistic beaming on the RLF was analyzed in a series of papers (Urry & Shaver 1984; Urry et al. 1991; Urry & Padovani 1991, 1995). If the RLF of the parent population of unbeamed objects is described by a broken power law, the break will produce a change of slope in the BL Lac RLF at $\sim \delta_{\text{max}} \times P_{\text{br}, \text{LRP}}$, where $\delta_{\text{max}}$ is the maximum value of the jet Doppler factor distribution. The ratio between $P_{\text{br}, \text{LRP}}$ and $P_{\text{br}, \text{BL Lac}}$ is a factor $\sim 10^3$, which suggests a value of the Doppler factor $\delta_{\text{max}} \sim 10$, remarkably consistent with the typical results obtained from the observations and the model predictions (e.g., Ghisellini et al. 1993, Savolainen et al. 2010). This analysis implicitly assumes that all LRP AGN produce relativistic jets, a requirement that is not necessarily met by the objects at the very faint end of the RLF. The consistency between the estimates of the Doppler factor we just obtained with the theoretical expectations appears to confirm the overall validity of this assumption.

How can we improve our knowledge of the RLF at low power? For LRP AGN the lower limit to the break power, $\log (P_{\text{br}, \text{LRP}}/\text{W Hz}^{-1}) \sim 20.5$, is not far from what is currently accessible to radio observations of large sample of galaxies such as the NVSS. A factor of $\sim 10$ improvement in the flux threshold is already accessible to the JVLA and it will be sufficient to measure directly the RLF of LRP AGN below the break value we predicted. While waiting for such a survey it is possible to take advantage of the stacking technique (e.g., White et al. 2007) to measure the median radio luminosity of the population of massive elliptical galaxies at sub-mJy levels. In case the number density presents a peak in its distribution, as our results suggest, this median luminosity is predicted to be located close to the peak value.

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.. $\Gamma = (1 - \beta^2)^{-1/2}$ is the bulk Lorentz factor, $\beta$ is the velocity in units of the speed of light, and $\theta$ is the viewing angle. The exact value of the $\delta$ exponent depends on the geometry of the emitting region.\[2\]
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