



Publication Year	2016
Acceptance in OA@INAF	2020-05-04T15:54:02Z
Title	Dark bubbles around high-redshift radio-loud active galactic nucleus
Authors	GHISELLINI, Gabriele; Sbarrato, Tullia
DOI	10.1093/mnrasl/slw089
Handle	http://hdl.handle.net/20.500.12386/24463
Journal	MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY
Number	461



Dark bubbles around high-redshift radio-loud active galactic nucleus

G. Ghisellini¹★ and T. Sbarro²★

¹INAF – Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate, Italy

²Univ. di Milano Bicocca, Dip. di Fisica G. Occhialini, Piazza della Scienza 3, I-20126 Milano, Italy

Accepted 2016 May 4. Received 2016 May 4; in original form 2016 March 15

ABSTRACT

At redshift larger than 3 there is a disagreement between the number of blazars (whose jet is pointing at us) and the number of expected parents (whose jet is pointing elsewhere). Now we strengthen this claim because (i) the number of blazars identified within the Sloan Digital Sky Survey (SDSS)+Faint Images of the Radio Sky at Twenty-cm (FIRST) survey footprint increased, demanding a more numerous parent population, and (ii) the detected blazars have a radio flux large enough to be above the FIRST flux limit even if the jet is slightly misaligned. The foreseen number of these slightly misaligned jets, in principle detectable, is much larger than the radio-detected sources in the FIRST+SDSS survey (at redshift larger than 4). This argument is independent of the presence of an isotropic radio component, such as the hotspot or the radio lobe, and does not depend on the bulk Lorentz factor Γ . We propose a scenario that ascribes the lack of slightly misaligned sources to an overobscuration of the nucleus by a ‘bubble’ of dust, possibly typical of the first high-redshift quasars.

Key words: accretion, accretion discs – galaxies: active – galaxies: jets – quasars: general.

1 INTRODUCTION

Blazars (flat spectrum radio quasars, FSRQs, and BL Lac objects) produce most of their non-thermal radiation in jets whose plasma is moving relativistically at small angles θ from the line of sight. How small the viewing angle must be for a source to be a blazar is not defined exactly, but we have proposed to use $\theta < 1/\Gamma$, where Γ is the bulk Lorentz factor of the emitting plasma. Under this definition, for a jet pointing in our direction within an angle $1/\Gamma$ there must exist $2\Gamma^2$ other sources with their jets pointing elsewhere: these sources form the parent population of blazars, and are usually associated with the Fanaroff–Riley type I (FR I; low luminosity) and Fanaroff–Riley type II (FR II; high luminosity) radio galaxies (Fanaroff & Riley 1974).

Volonteri et al. (2011, hereafter V11) pointed out the difficulties in reconciling the number of blazars observed at high redshifts with the number of the expected parent population. The flux of these sources is less beamed and amplified with respect to the aligned sources, and for large enough θ is even de-beamed, but the extended structures at the end of the jets (hotspots and lobes), that emit isotropically, could be bright enough to be detectable, especially if the jet is powerful (FR II), as are all the jets detected at high redshifts.

V11 also pointed out that the disagreement between the number of blazars and their parents occurs only for redshifts $z \gtrsim 3$. This was based on two cross-correlated catalogues: the Fifth Quasar

Catalog (Schneider et al. 2010) of the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Faint Images of the Radio Sky at Twenty-cm (FIRST; White et al. 1997). The SDSS Quasar Catalog is a spectroscopic, magnitude-limited quasar survey ($m_i < 19$ or 21 for low- and high-redshift quasars) and FIRST is a Very Large Array (VLA) radio survey complete above 1 mJy at 1.4 GHz. The common sky area is 8770 deg². The quasars belonging to the two samples (that we will collectively call SDSS+FIRST) have been studied by Shen et al. (2011). According to this study, and listed in Table 2, in the redshift bin $4 < z < 5$ there are 1192 quasars, 49 of which are radio detected. Of these, at least six are blazars. Above redshift 5 there are 56 quasars, of which four are radio detected, and two of these are blazars.

If we take the six blazars with redshift between 4 and 5, we expect $(1200 \pm 480)(\Gamma/10)^2$ misaligned jets (assuming an uncertainty of $\sqrt{6}$ in the number of observed blazars in this redshift bin), but we see a total of only 49 radio sources above 1 mJy. Above $z > 5$, the two observed blazars should correspond to $(400 \pm 280)(\Gamma/10)^2$ parents, but we see a total of only four sources above 1 mJy. These numbers strengthen the problem pointed out in V11, because, since then, more radio sources in the SDSS+FIRST turned out to be blazars (see e.g. Sbarro et al. 2013, 2015; Ghisellini et al. 2014a).

V11 proposed three possible solutions to this disagreement: (i) the bulk Lorenz factor is much lower than what it is at $z \lesssim 3$. To reconcile the numbers, we would need $\Gamma = 2$, which is inconsistent with the observed properties of high- z blazars (see e.g. Lister et al. 2013; Ghisellini & Tavecchio 2015); (ii) there is a (yet unknown) bias in the SDSS+FIRST survey against the detection of high- z radio-loud sources. For instance, the isotropic radio structure could

* E-mail: gabriele.ghisellini@brera.inaf.it (GG); tullia.sbarro@unimib.it (TS)

be young and compact, self-absorbed at frequencies larger than 10 GHz (in the rest frame), and therefore be below the 1 mJy flux detection limit of the FIRST; (iii) the SDSS+FIRST survey misses the detection of a large population of parents because their optical flux is absorbed by dust. A fourth solution would be to postulate the absence of the hotspot and lobe in these sources, or that these structures are very faint in the radio band for redshifts larger than 3.

In fact, the $\propto (1+z)^4$ scaling of the cosmic background radiation (CMB) energy density can greatly affect the radio emission of extended structures, as explored by Mocz, Fabian & Blundell (2011) and by Ghisellini et al. (2013, 2015). Consider two sources at different redshifts that have the same size, magnetic field, and that are energized by the same injected power. The higher z source will have a fainter radio emission and a stronger X-ray luminosity than the lower z source. This is because the emitting electrons will preferentially cool through inverse Compton scattering off CMB seed photons rather than producing synchrotron emission. The quenching of the radio emission can help to reconcile the disagreement between the number of high- z blazars and the corresponding number of expected parents, but in this Letter we point out that this effect is not enough.

In fact we will point out that also the sources whose jet is slightly misaligned can produce a flux above the threshold limit of the radio survey. This is independent of the CMB energy density. If a jet emits a radio flux of – say – 200 mJy and it is observed at a given (small) θ , there should be other similar jets observed at larger viewing angles but whose radio flux is larger than the flux limit of the survey (in our case, 1 mJy). Even these sources are missing. The problem is even more severe because we will show that the expected number of these sources is independent of the bulk Lorentz factor. We believe that this calls for a revision of our basic understanding of these high- z sources.

2 SLIGHTLY MISALIGNED JETS

We define as blazar a source whose jet is observed at a viewing angle $\theta \leq 1/\Gamma$. At $\theta = 1/\Gamma$, the Doppler factor is

$$\delta \equiv \frac{1}{\Gamma(1 - \beta \cos \theta)} = \Gamma. \quad (1)$$

Smaller angles have larger Doppler factors (at 0° , $\delta \sim 2\Gamma$), but the probability P to observe a jet pointing exactly at us is vanishingly small ($P \propto \theta^2$). Assume that a source, in the comoving (primed) frame, emits a monochromatic flux $F'(\nu') = F'(\nu)/\delta$. Then the observer at the Earth will see a flux $F(\nu)$:

$$F(\nu) = \delta^p F'(\nu). \quad (2)$$

The exponent p can have different values. If the emission is a power law of spectral index α [i.e. $F(\nu) \propto \nu^{-\alpha}$], we have among the several possibilities.

(i) $p = 2 + \alpha$: in this case the jet emits between two locations that are stationary in the observer frame. The radiation is emitted isotropically in the comoving frame. Sometimes this is called the finite lifetime jet case.

(ii) $p = 3 + \alpha$: this is the case of a moving blob, emitting isotropically in the comoving frame.

(iii) $p = 4 + 2\alpha$: the jet is a moving blob emitting inverse Compton radiation using seed photons that are produced externally to the jet (the so-called external Compton mechanism), and that are distributed isotropically in the observer frame. The inverse Compton flux is not isotropic in the comoving frame, but it is enhanced in

the forward direction (see Dermer 1995). This changes the pattern of the radiation as seen in the observer frame with respect to the previous ($p = 3 + \alpha$) case.

Assuming that the maximum observable boost is for $\sin \theta \sim 1/\Gamma \rightarrow \cos \theta = \beta$:

$$F_{\max}(\nu) = \delta_{\max}^p F'(\nu) = F'(\nu)\Gamma^p. \quad (3)$$

The maximum viewing angle θ_c at which this source can be seen is set by

$$F_{\min}(\nu) = \delta_{\min}^p F'(\nu) = \frac{F'(\nu)}{[\Gamma(1 - \beta \cos \theta_c)]^p}. \quad (4)$$

Therefore the ratio of the maximum to the minimum fluxes gives

$$\frac{F_{\max}(\nu)}{F_{\min}(\nu)} = \left[\frac{\delta_{\max}}{\delta_{\min}} \right]^p = [\Gamma^2(1 - \beta \cos \theta_c)]^p. \quad (5)$$

This gives the maximum viewing angle as

$$\cos \theta_c = \frac{1}{\beta} - \frac{1}{\beta \Gamma^2} \left[\frac{F_{\max}(\nu)}{F_{\min}(\nu)} \right]^{1/p}, \quad \beta > 0. \quad (6)$$

Now we can calculate the ratio of the number of sources oriented within θ_c to the sources oriented within $\theta = 1/\Gamma$:

$$\begin{aligned} R &\equiv \frac{\# \text{ within } \theta_c}{\# \text{ within } 1/\Gamma} = \frac{\int_{\cos \theta_c}^1 d \cos \theta}{\int_{\beta}^1 d \cos \theta} = \frac{1 - \cos \theta_c}{1 - \beta} \\ &= (1 + \beta)\Gamma^2 \left\{ 1 - \frac{1}{\beta} + \frac{1}{\beta \Gamma^2} \left[\frac{F_{\max}(\nu)}{F_{\min}(\nu)} \right]^{1/p} \right\} \\ &\sim 2 \left[\frac{F_{\max}(\nu)}{F_{\min}(\nu)} \right]^{1/p} - 1, \end{aligned} \quad (7)$$

where the last approximate equality is valid for $\beta \rightarrow 1$. In this limit the ratio R is not dependent on Γ .

As an example, assume that the brightest radio source in a sample is a blazar with $F_{\max}(\nu) = 100$ mJy and the limiting flux of the same sample is 1 mJy. Assume $\alpha = 0$ and $p = 3$. The very existence of this blazar implies the existence of other $[2 \times 100^{1/3} - 1] = 8.3$ observed jets, independent of the presence or absence of isotropic extended hotspots/lobes. The limiting viewing angle does depend on Γ , and is $\theta_c \sim 17.5^\circ$ (if $\Gamma = 10$) or 8.7° (if $\Gamma = 20$).

3 PREDICTED VERSUS OBSERVED RADIO-LOUD SOURCES

We can apply the calculations detailed in the previous section to all the blazars in a sample. Adopting for each of them its radio flux $F_i(\nu)$ and the same flux limit (i.e. 1 mJy) we can calculate for each blazar how many slightly misaligned jets we expect to be observable, and then sum up to obtain the total expected ratio between the total detectable sources and the total observed blazars:

$$R_{\text{tot}} = \sum_{i=1}^{i=6} 2 \left[\frac{F_i(\nu)}{1 \text{ mJy}} \right]^{1/p} - 1. \quad (8)$$

In few previous works we classified a number of blazar candidates included in the SDSS+FIRST (Sbarra et al. 2012, Sbarra et al. 2013, 2015; Ghisellini et al. 2014b). To identify the most reliable candidates, we selected the $z > 4$ quasars with a radio loudness $R = F_{5 \text{ GHz}}/F_{2500 \text{ \AA}} > 100$ from SDSS+FIRST. In fact, among radio-loud sources, a more extreme radio-to-optical dominance is a first indication of a jet oriented roughly towards us. X-ray follow-up

Table 1. The top part of the table lists the known blazars at $z \geq 4$ in the SDSS+FIRST spectroscopic catalogue (Shen et al. 2011). The bottom part lists (in italic) other three blazars present in the photometric catalogue of the SDSS+FIRST, but not in the spectroscopic one. They are shown for completeness, but we ignore them in the following. The radio loudness R is defined as $F_{\text{5 GHz}}/F_{2500 \text{ \AA}}$, where $F_{\text{5 GHz}}$ and $F_{2500 \text{ \AA}}$ are the monochromatic rest-frame fluxes at 5 GHz and at 2500 Å, respectively. F_R is the radio flux density at 1.4 GHz in mJy.

SDSS name	z	R	F_R
083946.22+511202.8	4.390	285	41.6
102623.61+254259.5	5.304	5200	239.4
114657.79+403708.6	5.005	1700	12.5
130940.70+573309.9	4.268	133	11.3
132512.49+112329.7	4.412	879	71.1
142048.01+120545.9	4.034	1904	87.3
151002.92+570243.3	4.309	13 000	255.0
222032.50+002537.5	4.205	4521	116.0
<i>143023.7+420436</i>	<i>4.715</i>	<i>5865</i>	<i>215.6</i>
<i>171521.25+214531.8</i>	<i>4.011</i>	<i>30 000</i>	<i>396.0</i>
<i>213412.01 – 041909.9</i>	<i>4.346</i>	<i>24 000</i>	<i>295.1</i>

observations allowed us to confirm the blazar classification of the most radio-loud candidates (and more observations will follow). From these studies, we concluded that there are (at least) six blazars in the SDSS+FIRST spectroscopic catalogue at $4 \leq z < 5$, and two at $z > 5$. These are listed in the top part of Table 1. Note that the three sources included in the SDSS+FIRST, but not in its spectroscopic catalogue (classified in Ghisellini et al. 2015) are here excluded because they do not have the necessary optical flux to enter the SDSS+FIRST spectroscopic, flux-limited sample. They are listed in the bottom part of Table 1.

We are confident that these blazars are indeed observed at an angle $\theta < 1/\Gamma$. In fact the X-ray flux and spectrum (due to external Compton) are dependent on the viewing angle in a stronger way than the radio (synchrotron) flux, as mentioned in Section 2 (the p -value is different). At high redshift (and in the absence of a detection in the γ -ray band), this is the best diagnostic to derive the jet orientation (see fig. 3 of Sbarato et al. 2015 showing how the spectral energy distribution changes by small changes in the viewing angle). Furthermore, in the case of B2 1023+25, the small viewing angle and large Lorentz factor were confirmed by the European VLBI (EVN) observations by Frey et al. (2015).

The existence of these blazars, compared with the whole SDSS+FIRST radio-detected sample, highlights a large discrepancy regarding the number of slightly misaligned jets. As listed in Table 2, the radio fluxes of the six blazars allow to predict a total of 616 ± 246 [$(6 \pm \sqrt{6}) \times R_{\text{tot}}(p=2)$] or 270 ± 108 [$(6 \pm \sqrt{6}) \times R_{\text{tot}}(p=3)$] jetted sources detectable in the SDSS+FIRST survey in the $4 \leq z < 5$ redshift bin. At $z > 5$, this number is 72 ± 50 ($p=2$).

Table 2. Numbers of radio-detected quasars in the SDSS+FIRST spectroscopic sample and number of predicted misaligned objects. We have applied equation (8) for each blazars considering its actual radio flux and the limiting flux of 1 mJy of the FIRST survey. For each blazar, there are $2\Gamma^2 \sim 338(\Gamma/13)^2$ jets pointing in other directions. The number of blazars refers to the objects spectroscopically observed for the construction of the catalogue. There are other high- z blazars in the SDSS+FIRST sky area that were photometrically detected, but that were not followed up spectroscopically (see Table 1 and Ghisellini et al. 2015).

	# Total	# Radio det.	# Blazars	Obs. ratio	$R_{\text{tot}}(p=2)$	$R_{\text{tot}}(p=3)$
$4 \leq z < 5$	1192	49	6	8.2	102.7	45
$z \geq 5$	56	4	2	2	36	15

or 30 ± 21 ($p = 3$). We believe that this is a severe disagreement, because of the following.

(i) The number of expected slightly misaligned objects derived from the known blazars is robust, because independent of Γ .

(ii) Since the flux comes from the jet, these objects are observed as point-like sources. This bypasses the problem of associating one (or two, in the case of a double radio source) radio objects not coincident with a SDSS source. Furthermore, point-like sources are easier to detect with respect to extended ones.

(iii) All high- z blazars have their optical flux completely dominated by the accretion disc radiation. The synchrotron emission (that can be depressed more than the radio in slightly misaligned sources, since $\alpha \sim 1$) does not contribute significantly to the optical flux. This implies that slightly misaligned sources should in principle be included in the SDSS Quasar Catalog.

(iv) The presence of a dusty torus should not affect the optical flux, as long as its opening angle is similar to lower redshift sources. This implies that the optical emission, in a standard scenario, should not be obscured.

4 OBSCURING BUBBLES: A WAY OUT

The discrepancy between the predicted and observed number of sources that have slightly misaligned jets is serious, and calls for an explanation. In addition, we are not aware of any instrumental selection effect strongly biasing our sample. The possibility that were proposed previously by V11 aimed to account for the lack of extended and isotropically radio sources, namely the foreseen parent population of high- z blazars. To explain these (still missing) sources we can envisage two possible reasons: (i) the observational difficulty to detect a weak extended radio source at some angular distance from a point-like optical object and (ii) the ‘radio quenching’ effect due to the enhanced CMB radiation energy density that cools more efficiently the emitting electrons through the inverse Compton mechanisms and that weakens their radio emission.

However, the regions of the jet producing the 1.4 GHz radio flux ($\gtrsim 7$ GHz rest frame) are not affected by the ‘quenching’ of the radio due to the CMB radiation. This is because they have a magnetic energy density much larger than the CMB one, even taking into account the Γ^2 enhancement due to the relativistic motion of the emitting plasma.

At $z = 4$, the CMB energy density is $U_{\text{CMB}} \sim 2.6 \times 10^{-10} \text{ erg cm}^{-3}$. In the comoving frame, this is enhanced by a factor $\sim \Gamma^2$, thus reaching $U' = 2.6 \times 10^{-8}(\Gamma/10)^2 \text{ erg cm}^{-3}$. Most of the observed radiation from the jet is produced in a compact region, where the magnetic field is around 3 G, and the observed self-absorption frequency is $\nu_t \sim 3 \times 10^{12} \text{ Hz}$ (rest frame, see e.g. Ghisellini & Tavecchio 2015). In the case of a flat radio spectrum, the self-absorption frequency scales as R^{-1} , where R is the distance from the black hole. This is the same dependence of the dominant component of the magnetic field B . Therefore in the region

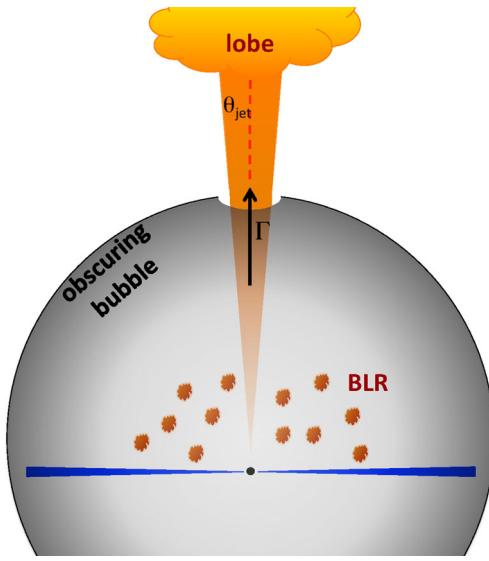


Figure 1. Cartoon of the proposed scenario (not to scale). The grey sphere is the obscuring bubble, pierced by the jet (in orange). The accretion disc (blue) and the BLR (brown) are unobscured only if the source is observed down the jet.

self-absorbing at 7 GHz (rest frame) B should be ~ 6 mG, and its energy density $U_B = B^2/(8\pi) \sim 1.4 \times 10^{-6}$. Since $U_B > U'_{\text{CMB}}$, there is no ‘quenching’ of the synchrotron emission of the jet.

4.1 The proposed scenario

To solve the tension between predicted and observed sources, we propose a scenario that follows the ideas put forward by Fabian (1999). At redshifts larger than ~ 4 , jetted sources hosting a black hole with mass $M \gtrsim 10^9 M_\odot$ ¹ are completely (i.e. 4π) surrounded with obscuring material (see the cartoon in Fig. 1). Only the jet can pierce through this material and break out. Observers looking down the jet can see the nuclear emission from the accretion disc and the broad emission lines. For observers looking with viewing angles even only slightly larger than $\theta_j \approx 1/\Gamma$, the optical emission (including broad lines) is absorbed, the flux is fainter, and the source cannot enter the SDSS Catalog. The absorbed radiation is reradiated in the infrared.

Even if the hotspots or the lobes were indeed emitting a radio flux above the 1 mJy level at the observed 1.4 GHz frequency, there would be no source in the SDSS to match with if the jet is only slightly misaligned. The quasi-spherical dusty structure (hereafter ‘obscurring’ or ‘dark bubble’) can cover the nuclear region until the accretion disc radiation pressure blows it away. This can occur at a threshold luminosity $L_{\text{th}} = \eta_d \dot{M} c^2$.

5 DISCUSSION

Let us assume that the obscuring bubbles exist not only in jetted sources, but are common to all high-redshift quasars, including radio-quiet ones. The evolution in time of the obscuring bubbles and the central black hole mass could however be different in jetted and non-jetted sources.

¹ Only the quasars with very massive black holes can be detected in the SDSS.

In fact, the presence of a jet could affect the accretion efficiency η_d , defined as $L_d = \eta_d \dot{M} c^2$: part of the dissipation of the gravitational energy could amplify the magnetic field instrumental to launch the jet. In other words, while in the case of non-jetted active galactic nucleus (AGN) the gravitational energy is dissipated only through radiation from the disc (i.e. $\eta_d = \eta$), radio-loud sources could use a fraction f of the released gravitational energy to heat the disc, and the remaining fraction $(1 - f)$ to launch the jet (Jolley & Kuncic 2008; Jolley et al. 2009):

$$\eta_d = f \eta. \quad (9)$$

This condition could lead to different evolution patterns of the obscuring bubbles. If we assume an Eddington-limited accretion until the obscuring bubble is blown away by the reached L_{th} , the mass growth rate of the black hole is

$$\dot{M} = \frac{dM}{dt} = \frac{1 - \eta}{\eta_d} \frac{L_{\text{Edd}}}{c^2} = \frac{1 - \eta}{\eta_d} k M; \quad k = \frac{4\pi G m_p}{\sigma_T c}, \quad (10)$$

where m_p is the proton mass, σ_T is the Thomson cross-section, and G is the gravitational constant. Therefore the black hole mass evolves as

$$M(t; \eta_d) = M_0 \exp \left\{ \frac{1 - \eta}{\eta_d} k t \right\}. \quad (11)$$

The threshold luminosity can therefore be expressed as a function of time:

$$\begin{aligned} L_{\text{th}} &= 1.3 \times 10^{38} \frac{M_{\text{th}}(t; \eta_d)}{M_\odot} \text{ erg s}^{-1} \\ &= 1.3 \times 10^{38} \frac{M_0}{M_\odot} \exp \left\{ \frac{1 - \eta}{\eta_d} k t_{\text{th}} \right\} \text{ erg s}^{-1} \end{aligned} \quad (12)$$

from which we can derive how much time it takes for a massive black hole to reach the threshold luminosity itself,

$$t_{\text{th}} = \frac{\eta_d}{k(1 - \eta)} \ln \left\{ \frac{L_{\text{th}}}{1.3 \times 10^{38} M_0 / M_\odot} \right\} \propto f \frac{\eta}{1 - \eta}. \quad (13)$$

Considering the difference in the use of gravitational energy in jetted and non-jetted AGN, there is a clear difference in the time needed for a source to blow away the dark bubble: if radio-loud AGN dissipate in radiation only $f = 1/2$ of the released gravitational energy, *radio-loud AGN can get rid of their dark bubbles in half time, compared to non-jetted sources*.

On the other hand, the black hole mass, at the time t_{th} , is independent of f . For illustration, let us compare jetted and non-jetted sources of equal seed black hole mass M_0 , all emitting at their Eddington luminosity. Jetted sources have black holes that grow faster (if $\eta_d = f\eta$). Therefore, at any given time, their Eddington luminosity is larger than that of the radio-quiet ones accreting with the same total η , but with $\eta_d = \eta$. Fig. 2 shows the growth of the black hole for different values of η and η_d , assuming that the accretion starts at $z = 20$ on a seed black hole mass of $100 M_\odot$. Assuming a threshold luminosity of $L_{\text{th}} = 10^{47}$ erg s $^{-1}$, this is reached first by the jetted sources. Fig. 2 shows also the case of a total efficiency $\eta = 0.1$. Although we note the same trend (jetted sources with $\eta_d = 0.05$ grows faster), we can note that in this case the threshold luminosity L_{th} is reached at much larger redshifts. At $z > 4$, all jetted sources would have lost their absorbing bubble, and would be visible. One could also have jetted sources with $\eta = 0.3$ (and a smaller η_d), but radio-quiet sources with $\eta = \eta_d \sim 0.1$. In this case the radio-quiet ones could blow out the absorbing bubbles earlier than the jetted sources. This does not affect the general picture we are proposing, but it seems unlikely that at very early times, when we have large

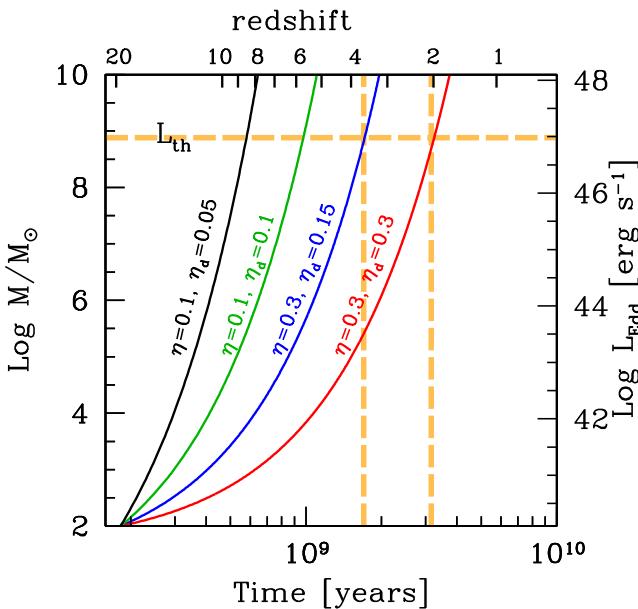


Figure 2. Growth of a black hole mass for different values of the total efficiency η and disc efficiency η_d . The horizontal dashed line corresponds to an assumed $L_{\text{th}} = 10^{47} \text{ erg s}^{-1}$. The vertical dashed lines correspond to the times (bottom axis) and the redshift (top axis) when the disc luminosity reaches L_{th} .

accretion rates, the spin of the black hole (that controls the efficiency η) is less than its maximum value (Thorne 1974), for all kind of objects. Major mergings could reset the black hole spin to values smaller than unity, but the rarity of very large black hole masses and the short available time (of the order of 1 Gyr) makes this possibility unlikely.

In the case we are discussing (all sources have $\eta = 0.3$, but η_d of radio quiet is larger than in radio loud), we have an interesting consequence. If we consider very large black hole masses (larger than $10^9 M_\odot$), jetted sources become fully visible in the optical at earlier times than radio-quiet objects. Even if the *intrinsic* ratio N_L/N_Q between the number of jetted and non-jetted sources were constant in time (e.g. $N_L/N_Q = 0.1$, as at low redshift), we would infer at $z \gtrsim 4$ a radio-loud fraction larger than N_L/N_Q from the blazar population. We stress that this would be true only if we consider large black hole masses that need ~ 1 Gyr to blow up the absorbing bubble. If the critical luminosity L_{th} is smaller, it can be produced by a black hole of a smaller mass, that is reached at earlier times (larger redshifts). In this case, at $z \sim 4$, these sources are all visible, since they have already blown up their bubbles.

This dark bubble scenario makes a simple prediction: most high- z parents of blazars with large black hole masses should be absorbed in the optical band, but should be very bright in the infrared. In this respect we can look at high- z radio galaxies. Indeed, there is already one interesting example, 4C 41.17 ($z \sim 3.8$), that is extremely bright in the far-infrared (with flux densities ranging from $23.4 \pm 2.4 \mu\text{Jy}$

at $3.6 \mu\text{m}$ to $36.5 \pm 3.5 \mu\text{Jy}$ at $8 \mu\text{m}$ and a luminosity exceeding $10^{47} \text{ erg s}^{-1}$), but fainter in the optical by a factor of ~ 30 (Chambers, Miley & van Breugel 1990; van Breugel et al. 1998; Seymour et al. 2007; Wu et al., in preparation). This is not a proof of a 4π absorbing bubble, but suggests that the absorbing material intercepts a larger fraction of the visible light, compared to local radio galaxies.

ACKNOWLEDGEMENTS

We thank the referee and Ann Wehrle for their useful comments and M. Lucchini for discussions. We acknowledge financial contribution from the agreement ASI-INAF I/037/12/0 (NARO 15) and from the CaRiPlO Foundation and the regional Government of Lombardia for the project ID 2014-1980 ‘Science and technology at the frontiers of γ -ray astronomy with imaging atmospheric Cherenkov telescopes’.

REFERENCES

- Chambers K. C., Miley G. K., van Breugel W. J. M., 1990, ApJ, 363, 21
- Dermer C. D., 1995, ApJ, 446, L63
- Fabian A. C., 1999, MNRAS, 308, L39
- Fanaroff B. L., Riley J. M., 1974, MNRAS, 167, 31p
- Frey S., Paragi Z., Fogasy J. O., Gurvits L. I., 2015, MNRAS, 446, 2921
- Ghisellini G., Haardt F., Della Ceca R., Volonteri M., Sbarato T., 2013, MNRAS, 432, 2818
- Ghisellini G., Celotti A., Tavecchio F., Haardt F., Sbarato T., 2014a, MNRAS, 438, 2694
- Ghisellini G., Sbarato T., Tagliaferri G., Foschini L., Tavecchio F., Ghirlanda G., Braito V., Gehrels N., 2014b, MNRAS, 440, L111
- Ghisellini G., Haardt F., Ciardi B., Sbarato T., Gallo E., Tavecchio F., Celotti A., 2015, MNRAS, 452, 3457
- Ghisellini G., Tavecchio F., 2015, MNRAS, 448, 1060
- Jolley E. J. D., Kuncic Z., 2008, MNRAS, 386, 989
- Jolley E. J. D., Kuncic Z., Bicknell G. V., Wagner S., 2009, MNRAS, 400, 1521
- Lister M. L. et al., 2013, AJ, 146, 120
- Mocz P., Fabian A. C., Blundell K. M., 2011, MNRAS, 413, 1107
- Sbarato T. et al., 2012, MNRAS, 426, L91
- Sbarato T. et al., 2013, ApJ, 777, 147
- Sbarato T., Ghisellini G., Tagliaferri G., Foschini L., Nardini M., Tavecchio F., Gehrels N., 2015, MNRAS, 446, 2483
- Schneider D. P. et al., 2010, AJ, 139, 2360
- Seymour N. et al., 2007, ApJS, 171, 353
- Shen Y. et al., 2011, ApJS, 194, 45
- Thorne K. S., 1974, ApJ, 191, 507
- van Breugel W. J. M., Stanford S. A., Spinrad H., Stern D., Graham J. R., 1998, ApJ, 502, 614
- Volonteri M., Haardt F., Ghisellini G., Della Ceca R., 2011, MNRAS, 416, 216 (V11)
- White R. L., Becker R. H., Helfand D. J., Gregg M. D., 1997, ApJ, 475, 479
- York D. G. et al., 2000, AJ, 120, 1579