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SDSS J102623.61+254259.5: the second most distant blazar at $z = 5.3$

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ABSTRACT

The radio-loud quasar SDSS J102623.61+254259.5, at a redshift $z = 5.3$, is one of the most distant radio-loud objects. Since its radio flux exceeds 100 mJy at a few GHz, it is also one of the most powerful radio-loud sources. We propose that this source is a blazar, i.e. we are seeing its jet at a small viewing angle. This claim is based on the spectral energy distribution of this source, and especially on its strong and hard X-ray spectrum, as seen by *Swift*, very typical of powerful blazars. Observations by the Gamma-Ray Burst Optical/Near-Infrared Detector (GROND) and by the *Wide-field Infrared Survey Explorer* (*WISE*) allow us to establish the thermal nature of the emission in the near-IR–optical band. Assuming that this is produced by a standard accretion disc, we derive that it emits a luminosity of $L_{\rm d} \simeq 9 \times 10^{46}$ erg s^{-1} and that the black hole has a mass between 2 and 5 billion solar masses. This poses interesting constraints on the mass function of heavy ($>10^9$ M$_\odot$) black holes at high redshifts.

Key words: galaxies: active – quasars: general – quasars: individual: B2 1023+25 – X-rays: general.

1 INTRODUCTION

Blazars are active galactic nuclei (AGN) whose relativistic jets are seen at a small angle from our line of sight, smaller than $1/\Gamma$, where Γ is the bulk Lorentz factor of the emitting plasma. The radiation emitted by their jets is therefore strongly boosted, making them visible at high redshifts. The most distant blazar known is Q0906+6930 (Romani et al. 2004; Romani 2006) with a redshift $z = 5.47$. The spectral energy distribution (SED) of this source reveals both the thermal (i.e. strong optical emission lines and continuum) and boosted non-thermal [dominating in all bands but the near-IR (NIR) and optical] components. This is a common characteristic of powerful blazars at high redshift: the non-thermal emission is characterized by two broad humps, peaking at lower frequencies as the bolometric luminosity increases, making the underlying thermal emission visible in powerful blazars (since it stands between the two non-thermal humps; Ghisellini et al. 2010a,b). The high-energy hump, in these sources, peaks below 100 MeV, disfavouring its detection by the Large Area Telescope (LAT) instrument on-board the *Fermi* satellite (Atwood et al. 2009). Instruments observing in the hard X-ray band can instead have more chances to detect them, and in fact the Burst Alert Telescope (BAT) on-board the *Swift* satellite (Gehrels et al. 2004) has detected blazars up to larger redshifts compared to LAT (compare Ajello et al. 2009; Ackermann et al. 2011). Their X-ray spectrum is hard, [i.e. $\alpha_{\rm X} \lesssim 0.5$, assuming $F(\nu) \propto \nu^{-\alpha_{\rm X}}$], and this, together with a relatively strong X-ray to optical flux ratio, can be taken as a signature of the blazar nature of the source.

In this Letter, we suggest that SDSS J102623.61+254259.5, a radio-loud AGN at $z = 5.3$, is a blazar, i.e. the viewing angle is smaller than $1/\Gamma$. If so, then this source indicates the presence, at approximately the same redshift, of $\sim 2\Gamma^2$ other sources pointing in other directions, having similar intrinsic physical properties, including the black hole (BH) mass. Note that the flatness of the radio spectrum is not sufficient to guarantee the blazar nature of SDSS J102623.61+254259.5 since slightly misaligned sources (with respect to $1/\Gamma$) still show a flat radio spectrum, especially at relatively large radio frequencies (at $z = 5.3$, the observed 1.4 GHz flux corresponds to a rest-frame frequency of $\sim$9 GHz), where the radio lobe steep radio emission does not contribute. Evidence for its blazar nature is its very large radio loudness and very large radio luminosity. Observed by *Swift*, it revealed a strong and hard X-ray flux, confirming its blazar nature. Observations performed by the Gamma-Ray Burst Optical/Near-Infrared Detector (GROND; Greiner et al. 2008) and by the *Wide-field Infrared Survey Explorer*

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Table 1. GROND AB observed magnitudes of B2 1023+25, taken on 2012 April 16 (magnitudes not corrected for Galactic extinction). The first row gives the effective wavelength of the filter.

	g'	r'	i'	z'	J	H	K_s
$\lambda_{\rm eff}$ (Å)	4587	6220	7641	8999	12 399	16 468	21 706
AB magnitude	<24.0	22.07 ± 0.08	19.97 ± 0.03	19.86 ± 0.04	19.50 ± 0.10	19.23 ± 0.15	19.07 ± 0.21

(*WISE*) satellite (Wright et al. 2010), together with the Sloan Digital Sky Survey (SDSS; York et al. 2000) spectrum, allowed us to constrain the properties of the thermal emission.

In this work, we adopt a flat cosmology with $H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$ and $\Omega_{\rm M} = 0.3$.

2 B2 1023+25 AS A BLAZAR CANDIDATE

To obtain a sample of high-redshift blazar candidates, we selected a list of quasars included in the SDSS Data Release 7 (DR7) Quasar Catalog (Schneider et al. 2010), which have been analysed by Shen et al. (2011), with $z > 4$ and radio loudness $R > 100$, defined as $R = F(5\,{\rm GHz})/F(2500\,{\rm Å})$ (rest frame) in the work by Shen et al. We required a high radio loudness in order to preferentially select objects with the jet directed towards us. Through this selection, we obtained a sample of 31 sources with $z > 4$ including three with $z > 5$. The latter sources have no rest-frame 2500 Å flux and hence we calculated $F(2500\,{\rm Å})$ extrapolating from the continuum at $\lambda = 1350$ Å.

SDSS J102623.61+254259.5 (i.e. B2 1023+25) is the best blazar candidate from this list because of its very high redshift and extreme radio loudness ($R \sim 5200$). The precise value of the redshift is somewhat uncertain since $z = 5.284$ in NED, taken from the sixth data release of the Sloan survey (DR6), while $z = 5.3035$ in DR7 and $z = 5.266$ in DR8. In this Letter, we therefore assumed a value of $z = 5.3$. This is a known quasar, observed for the first time in the B2 Catalog of radio sources (Colla et al. 1972). The radio position of this source is RA = $10^{\rm h}26^{\rm m}23\overset{\rm s}{.}62$, Dec. = $+25°42'59\overset{''}{.}4$ and, according to the CRATES All-Sky Survey (Healey et al. 2007), the source has a flat spectrum with $\alpha_{1.4/4.8} = 0.489$ [between 1.4 and 4.8 GHz; $F(\nu) \propto \nu^{-\alpha}$] and $\alpha_{1.4/8.4} = 0.504$ with a radio flux of $F_{1.4\,{\rm GHz}} = 260.7$ mJy and $F_{8.4\,{\rm GHz}} = 105.7$ mJy. We retrieved a number of radio fluxes from archival data.[1] Moreover, B2 1023+25 is included in the *WISE* All-Sky Source Catalog,[2] with clear detections in the two bands at lower wavelengths of the instrument, i.e. $\lambda = 3.4$ and 4.6 μm.

We retrieved and analysed data of *Fermi*/LAT (Atwood et al. 2009) collected in the period from 2008 August 4 to 2012 June 14 (∼3.8 yr). Photons of class 2 (‘source’), with energies in the range 0.1–100 GeV, collected in a region of 10° radius from the source position, were analysed by using LAT Science Tools v. 9.27.1, Instrument Response Function P7 and the corresponding background maps. The followed procedures are described in detail in the analysis threads of the Fermi Science Support Center.[3] Particularly, the sources B2 1023+25 and Q0906+693 were fitted with a power-law model, together with any other source of the 2FGL catalogue (Nolan et al. 2012) within 10° from their sky coordinates. The analysis resulted in no detection for both sources, with a 5σ upper limit on the photon flux above 100 MeV of 3.0×10^{-9} photon cm^{-2} s^{-1}.

2.1 GROND observations

The seven-band GROND imager, mounted at the 2.2-m MPG/ESO telescope at La Silla Observatory (Chile), started observing B2 1023+25 on 2012 April 16 at 23:16:56 UTC. We carried out two 8-min observations simultaneously in all seven bands ($g', r', i', z', J, H, K_s$) for a total exposure time of 919 s in the optical as well as 960 s in the NIR bands. Observations were carried out at an average seeing of 1.2 arcsec and at an average airmass of 2.1. The source was clearly detected in all bands but g' for which an upper limit of 24.0 (AB magnitude) can be given.

The GROND optical and NIR image reduction and photometry were performed using standard IRAF tasks (Tody 1993) similar to the procedure described in Krühler et al. (2008). A general model for the point spread function of each image was constructed using bright field stars, and it was then fitted to the point source. The absolute calibration of the g', r', i' and z' bands was obtained with respect to the magnitudes of SDSS stars within the blazar field, while the calibration of the J, H and K_s bands was obtained with respect to magnitudes of the Two Micron All Sky Survey (2MASS) stars (Skrutskie et al. 2006).

Table 1 reports the observed AB magnitudes, not corrected for the Galactic extinction of $E(B - V) = 0.02$ from Schlegel, Finkbeiner & Davis (1998).

2.2 *Swift* observations

Since this is our best blazar candidate, we requested a ToO observation from the *Swift* team, in order to have X-ray data to confirm our hypothesis. The *Swift* satellite observed B2 1023+25 twice: on 2012 June 21 (ObsID: 00032500001) and 2012 June 22 (ObsID: 00032500002). Data of the X-ray Telescope (XRT; Burrows et al. 2005) and the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005) were downloaded from HEASARC public archive, processed with the specific *Swift* software included in the package HEASOFT v. 6.12[4] and analysed. The calibration data base was updated on 2012 July 16. We did not consider the data of BAT (Barthelmy et al. 2005), given the weak X-ray flux.

The total exposure on the XRT was of ∼10 ks and resulted in 26 counts. Given the low statistics, the fit with a power-law model with Galactic absorption ($N_{\rm H} = 1.50 \times 10^{20}$ cm^{-2}; Kalberla et al. 2005) was done by using the likelihood (Cash 1979). The output parameters of the model were $\Gamma = 1.1 \pm 0.5$ and an integrated observed flux $F_{0.3-10\,{\rm keV}} = (1.7 \pm 0.4) \times 10^{-13}$ erg cm^{-2} s^{-1}. The X-ray data displayed in the SED (Fig. 2) have been rebinned to have 3σ in each bin.

UVOT observed the source with two filters only: U, with 8.4 ks exposure, and $UVW1$, with 1.6 ks. Both resulted in no detection with 3σ upper limits of the observed magnitudes equal to 21.70 and 20.76 mag, respectively.

[1] ASI Science Data Center (ASDC): http://tools.asdc.asi.it/.
[2] Data retrieved from http://irsa.ipac.caltech.edu/.
[3] http://fermi.gsfc.nasa.gov/ssc/data/analysis/
[4] Including the XRT Data Analysis Software (XRTDAS) developed under the responsibility of the ASI Science Data Center (ASDC), Italy.

2.3 Estimate of the disc luminosity

We can calculate the disc luminosity $L_{\rm d}$ in two ways. The first is by assuming that the IR–optical flux is produced by a standard (Shakura & Sunjaev 1973) accretion disc, and finding the best $L_{\rm d}$ that accounts for the data. In this respect, for B2 1023+25 we have a rather good set of IR–optical data showing that the peak of the disc emission is at frequencies just below the absorption caused by intervening clouds (see Fig. 1). Since the overall $L_{\rm d}$ is about twice the νL_ν peak luminosity, we directly derive $L_{\rm d} = \simeq 9 \times 10^{46}$ erg s^{-1}.

The second method is through the broad emission lines, assuming that they re-emit a fraction C (i.e. their covering factor) of the ionizing luminosity, and assuming that the latter is provided by the accretion disc. The average value of C is around 0.1 (Baldwin & Netzer 1978; Smith et al. 1981), with a rather large dispersion. B2 1023+25 shows a prominent broad Lyα, which unfortunately is absorbed in its blue wing. Using only the red wing, and subtracting the continuum in the same frequency range (adopting a power-law model), we derive $L_{{\rm Ly}\alpha} \sim 2 \times 10^{45}$ erg s^{-1} and a full width at half-maximum of 4000 km s^{-1}. These are twice the values we measured for the red wing only, implicitly assuming that the line is intrinsically symmetric. The ratio between the entire BLR luminosity and $L_{{\rm Ly}\alpha}$ has been calculated by Francis et al. (1991) and Vanden Berk et al. (2001). The former gives a $L_{\rm BLR}/L_{{\rm Ly}\alpha} = 5.55$, while the latter gives a $L_{\rm BLR}/L_{{\rm Ly}\alpha} = 2.7$. Therefore, $L_{\rm BLR} \sim (5\text{–}10) \times 10^{45}$ erg s^{-1}. Finally, assuming $C = 0.1$, the estimate for the disc luminosity is $L_{\rm d} \sim (5\text{–}10) \times 10^{46}$ erg s^{-1}. Although this estimate is affected by relevant uncertainties (e.g. partially absorbed Lyα line and uncertain value of C), the estimated range encompasses the value found with the first method.

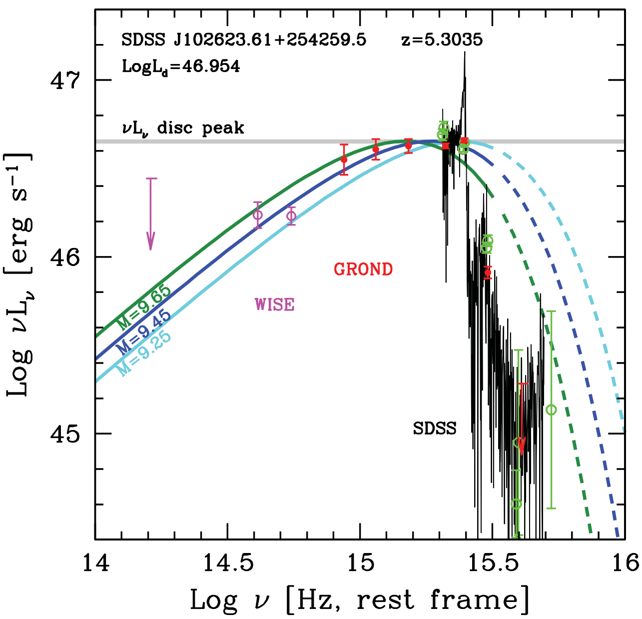

Figure 1. Optical–UV SED of B2 1023+25 in the rest frame, together with models of standard accretion disc emission. Data from *WISE* and GROND, and the SDSS spectrum are labelled. Green points are archival data taken from ASDC SED builder. The grey stripe indicates the νL_ν peak luminosity of the disc. We show the spectrum of three accretion disc models with the same luminosity and different $M_{\rm BH}$: $\log(M_{\rm BH}/{\rm M}_\odot) = 9.65$ (green), 9.45 (blue) and 9.25 (cyan). Note that outside this range of masses, the model cannot fit satisfactory the data.

3 BLACK HOLE MASS ESTIMATE

The flux and spectrum of the disc depend on the central BH mass $M_{\rm BH}$ and on the accretion rate $\dot{M}$. The latter is traced by the total disc luminosity $L_{\rm d} = \eta \dot{M} c^2$, with the efficiency parameter η assumed to be $\eta = 0.08$. If we measure $L_{\rm d}$ (hence $\dot{M}$), we are left with $M_{\rm BH}$ as the only remaining free parameter. For a given $\dot{M}$, the BH mass determines the peak frequency of the disc emission. A larger mass implies a larger disc surface and hence a lower temperature emitting a given luminosity. Therefore, for a fixed $L_{\rm d}$, a larger $M_{\rm BH}$ shifts the peak to lower frequencies. Then the best agreement with the data fixes $M_{\rm BH}$. We adopt $L_{\rm d} = 9 \times 10^{46}$ erg s^{-1}, as discussed above, and calculate the overall spectrum from a standard Shakura & Sunjaev (1973) disc.

Fig. 1 shows the data in the IR–optical band (as labelled) and three disc emission spectra calculated assuming the same $L_{\rm d}$ and three different mass values: $M_{\rm BH} = 4.5 \times 10^9\,{\rm M}_\odot$ (green line), $2.8 \times 10^9\,{\rm M}_\odot$ (blue) and $1.8 \times 10^9\,{\rm M}_\odot$ (cyan). Fig. 1 shows that, outside this range of masses, the model does not satisfactory reproduce the data any longer.

4 OVERALL SPECTRAL ENERGY DISTRIBUTION

Fig. 2 shows the overall SED of B2 1023+25, together with a fitting model. The latter is described in Ghisellini & Tavecchio (2009) and consists of one emitting zone, in which relativistic electrons, whose energy distribution is derived through a continuity equation, emit by the synchrotron and inverse-Compton processes. The accretion disc component is accounted for, as well as the IR emission reprocessed by, a dusty torus and the X-ray emission is produced by a hot thermal corona sandwiching the accretion disc. The parameters adopted to fit the SED are very similar to other powerful blazars studied and interpreted with the same model (Ghisellini et al. 2010a,b). The bulk Lorentz factor is $\Gamma = 14$ and the size of the emitting region

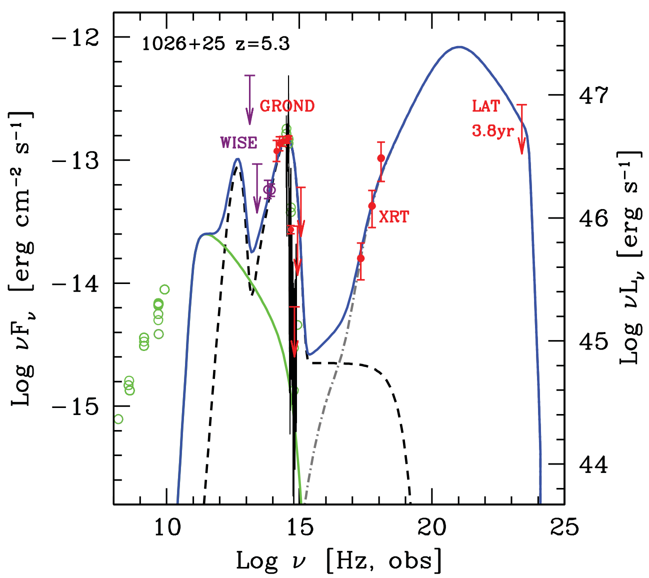

Figure 2. SED of B2 1023+25 together with the adopted model. Data from *WISE*, GROND, *Swift*/XRT and *Fermi*/LAT are labelled. Green points are archival data taken from ASDC SED builder. The solid green line is the synchrotron component of the model, the dashed black line is the torus+disc+X-ray corona component, the dot–dashed grey line is the external Compton contribution. The LAT upper limits is for 3.8 yr, 5σ.

is $R = 5 \times 10^{16}$ cm, located at a distance of 5×10^{17} cm from a BH of $M_{\rm BH} = 2.8 \times 10^9\,{\rm M}_{\odot}$. The magnetic field is $B = 2.1$ G. The main emission process for the X-ray and γ-ray non-thermal continuum is the inverse-Compton process off the emission line photons (i.e. external Compton). Since the emitting region is rather compact, its radio emission is self-absorbed (up to ∼600 GHz) and cannot account for the observed radio flux that must necessarily come from much larger zones. The Poynting flux carried by the jet is $P_{\rm B} \sim 10^{46}$ erg s^{-1}, and the power spent to produce the radiation we see is $P_{\rm r} \sim 3 \times 10^{45}$ erg s^{-1}. The power in the bulk motion of the emitting relativistic electrons is $P_{\rm e} \sim 2 \times 10^{44}$ erg s^{-1}, while the power in cold protons (assuming one proton per relativistic electron) is $P_{\rm p} \sim 5.5 \times 10^{46}$ erg s^{-1}.

4.1 Comparison with Q0906+6930

Fig. 3 shows how the SED of B2 1023+25 compares with the SED of Q0906+693. As can be seen, the two SEDs are very similar. The only, remarkable, difference could be in the γ-ray band, if the tentative EGRET association with Q0906+6930 is real. On the other hand, the upper limits of *Fermi*/LAT are the same for the two sources. This may suggest that the EGRET flux is not produced by Q0906+6930, although variations of even more than two orders of magnitude of the γ-ray flux are not uncommon for blazars (see e.g. Abdo et al. 2011; Ghirlanda et al. 2011).

Fig. 3 shows, as vertical stripes, the energy bands of XRT and of *NuStar* (Harrison et al. 2010). We report also the pre-launch estimated *NuStar* sensitivity for an exposure of 1 Ms. It is remarkable that both sources have an X-ray flux lying one order of magnitude above the *NuStar* sensitivity, making their detection possible even with a moderate exposure time and even at the high-energy limit of the instrument, i.e. at ∼80 keV. Note that 80 keV corresponds, in the rest frame of a $z = 5.3$ source, to ∼500 keV, which could be rather close to the peak of the high-energy emission.

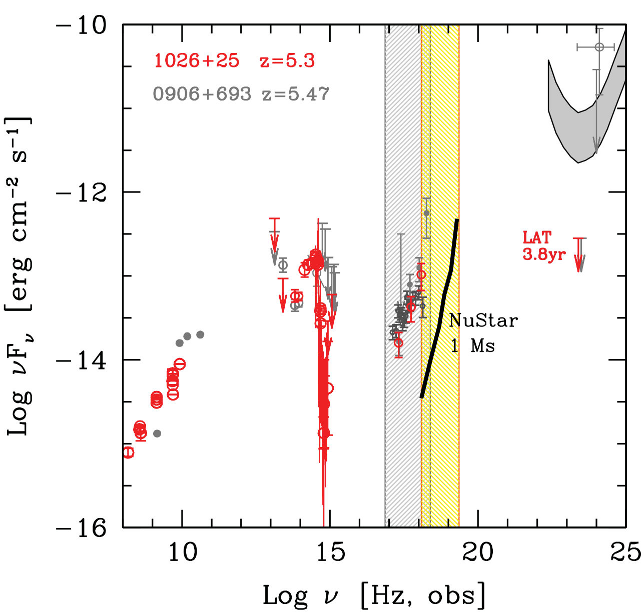

Figure 3. Comparison between the SED of B2 1023+25 (red symbols) and of Q0906+6930 (grey symbols). As can be seen, the two sources are very similar. The grey vertical stripe marks the [0.3–10 keV] energy range of XRT, while the yellow vertical stripe corresponds to the [5–80 keV] energy range of the *NuStar* satellite. The curved grey stripe corresponds to the sensitivity of *Fermi*/LAT after 1 yr of operation (5σ, lower bound) and of 3 months (10σ, upper bounds). We show the sensitivity (3σ) of the *NuStar* satellite for an exposure of 1 Ms.

5 DISCUSSION AND CONCLUSIONS

In this Letter, we propose that the radio-loud, high-redshift quasar B2 1023+25 is a blazar. It is the second most distant blazar known up to now, with redshift $z = 5.3$, that corresponds to an age of the Universe of 10^9 yr.

Both its thermal and non-thermal components are very luminous. In agreement with the blazar sequence (Fossati et al. 1998), the two broad non-thermal humps peak at small frequency. In particular, the hard X-ray spectrum and the upper limit in the γ-ray band constrain the high-energy component to peak in the MeV region of the spectrum. Therefore, this source, along with similar other powerful blazars, should have a relatively large hard X-ray flux and would have been an ideal target for planned hard X-ray instruments, such as *EXIST*, *Symbol-X* and *NHXM*, and it is a good target to be observed with the only orbiting satellite with focusing hard X-ray telescopes, i.e. *NuStar* (Harrison et al. 2010). The great sensitivity over its energy range [5–80 keV] enables it to detect the hard X-ray spectrum of this source, even if it cannot directly observe the peak of the high-energy hump.

Thanks to the good data coverage in the IR–optical range, given by the combination of the seven simultaneous optical–NIR filters of GROND coupled with *WISE* and SDSS data, we were able to estimate the central BH mass, which turned out to be between 2 and 5 billion solar masses. This relatively small range compares well with the virial estimates in general (that have at least a factor of ∼4 of uncertainties; see e.g. Vestergaard & Peterson 2006), and, in particular, it is the only method applicable for this source, where only a partially absorbed Lyα line is visible (and virial methods are not yet well calibrated in this case). NIR spectroscopy, and hence the detection of the broad C IV and Mg II lines, would help to improve the virial estimate of the BH mass and be a valuable cross-check of our estimate, based on the disc continuum.

It is remarkable to find radio-loud AGN hosting BH with such an extreme mass at an age of the Universe of only 10^9 yr. The discovery that B2 1023+25 is a blazar, together with that one of Q0906+693, in fact, implies the existence of an entire family of radio-loud, very massive quasars in the early Universe, whose jet is not aligned with our line of sight. Moreover, it is possible to roughly estimate the number of these objects and their spatial density.

The comoving density of heavy BHs at high redshifts of radio-loud sources has been studied by Volonteri et al. (2011), based on the 3 years BAT catalogue and the blazar luminosity function, in hard X-rays, derived by Ajello et al. (2009) and modified (beyond $z = 4.3$) by Ghisellini et al. (2010a). In the latter paper, the observational constrain on the blazar density with BHs heavier than $10^9\,{\rm M}_{\odot}$ in the redshift bin $5 < z < 6$ was based on the detection of only one object: Q0906+6930. Assuming it was the only blazar in the entire sky in this redshift bin, Ghisellini et al. (2010a) derived a comoving density of 2.63×10^{-3} Gpc^{-3} of blazars hosting a heavy BH in the $5 < z < 6$ bin (see fig. 15 in that paper).

B2 1023+25 was selected in the SDSS catalogue covered by FIRST observations, and the common area of the sky of these two surveys is 8770 deg^2. Its existence in this portion of the sky implies that the space density of blazars hosting an $M_{\rm BH} > 10^9\,{\rm M}_{\odot}$ BH is a factor of 40 000/8770 greater than estimated previously (increasing the corresponding comoving density to 1.2×10^{-2} Gpc^{-3}). In turn, the density of all radio-loud sources hosting an $M_{\rm BH} > 10^9\,{\rm M}_{\odot}$ BH must be a factor of $2\Gamma^2$ larger, namely $\sim 4.7(\Gamma/14)^2\,\mathrm{Gpc}^{-3}$ in the $5 < z < 6$ bin. Note that this is a lower limit since other high-redshift blazars could exist, but not yet identified as such.

Moreover, assuming that the ratio of radio-loud to radio-quiet AGN is ∼0.1, the SMBHs with $M_{\rm BH} > 10^9\,\mathrm{M}_{\odot}$ have to be *at least* 10^4 over the whole sky just after 10^9 yr from the birth of the Universe.

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