SDSS J114657.79+403708.6: the third most distant blazar at $z=5.0$

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ABSTRACT

The radio–loud quasar SDSS J114657.79+403708.6 at a redshift $z=5.0$ is one of the most distant radio–loud objects. The IR–optical luminosity and spectrum suggest that its black hole has a very large mass: $M = (5\pm1) \times 10^9 M_\odot$. The radio–loudness (ratio of the radio to optical flux) of the source is large (around 100), suggesting that the source is viewed at small angles from the jet axis, and could be a blazar. The-X–ray observations fully confirm this hypothesis, due to the high level and hardness of the flux. This makes SDSS J114657.79+403708.6 the third most distant blazar known, after Q0906+6930 ($z = 5.47$) and B2 1023+25 ($z = 5.3$). Among those, SDSS J114657.79+403708.6 has the largest black hole mass, setting interesting constraints on the mass function of heavy ($>10^9 M_\odot$) black holes at high redshifts.

Key words: galaxies: active – quasars: general; quasars: supermassive black holes – X–rays: general

1 INTRODUCTION

Since the radiation produced by relativistic jets is strongly boosted along the jet direction, objects whose jet is pointing at us are very bright, and can be seen up to high redshifts. The black hole at the center of the powerhouse of these sources can be very massive, sometimes exceeding $M = 10^{10} M_\odot$ (Ghisellini et al. 2009; 2010a). Therefore the hunt for high redshift blazars is an important field of research, allowing the census of heavy black holes in the early Universe. This can confirm or challenge existing theories of black hole formation, and even more so if we associate the presence of relativistic jets with a large black hole spin. In this case, in fact, the efficiency of accretion $\eta$ (the fraction of accreted mass transformed into radiation) is higher than for a non–rotating black hole, reaching a value of $\eta = 0.3$ for maximally rotating accreting black holes (see Thorne 1974). This implies that the Eddington luminosity is reached with a smaller accretion rate than for a non–rotating black hole. If the system is Eddington limited, this in turn implies a slower black hole growth. If a black hole seed starts to accrete at a redshift $z = 20$ at the Eddington rate maintaining a large spin, it can reach a billion solar masses only at $z < 4$ even for a seed mass as large as $10^6 M_\odot$ (see e.g. Ghisellini et al. 2013). The very fact of the existence of radio–loud sources with $M > 10^9 M_\odot$ at $z > 4$ is thus a problem.

These issues motivate our search of high redshift blazars, keeping in mind that for each blazar (i.e. viewing angle smaller than $1/\Gamma$, where $\Gamma$ is the jet bulk Lorentz factor) there must be other 2F$^{\text{LM}}$ sources whose jets are pointing in other directions.

Up to now there are two blazars known at $z > 5$: Q0906+6930 ($z = 5.47$, Romani et al. 2004; Romani 2006), and B2 1023+25 ($z = 5.3$, Sbarrato et al. 2012, 2013). The spectral energy distribution (SED) of these sources reveals both the thermal (i.e. strong optical emission lines and continuum) and the boosted non–thermal components. As in the majority of very powerful and high–$z$ blazars, the thermal disk emission becomes visible since it stands between the two non–thermal humps (the synchrotron one peaking in the sub-mm, and the high energy in the ~MeV band; Ghisellini et al. 2010a; 2010b). In these sources the X–ray spectrum is hard [i.e. $\alpha_X \sim 0.5$, assuming $F(\nu) \propto \nu^{-\alpha_X}$], 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 J114657.79+403708.6, a radio–loud AGN at $z = 5.005$, is a blazar, i.e. the viewing angle is smaller than $1/\Gamma$. Evidences for its blazar nature include its relatively large radio–loudness and its very large X–ray luminosity and hard X–ray spectrum, as measured by a pointed Swift observation. Infrared data collected by the WISE satellite (Wright et al. 2010), together with the Sloan Digital Sky Survey (SDSS; York et al. 2000) spectrum allowed to constrain the properties of the thermal emission.

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

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2 SDSS J114657.79+403708.6 AS A BLAZAR CANDIDATE

SDSS J114657.79+403708.6 (SDSS 1146+403 hereafter) belongs to the SDSS DR7 Quasar catalog (Schneider et al. 2010), that have been analysed by Shen et al. (2011). This sample contains ∼105,000 quasars. The area of the sky surveyed by the SDSS has been almost completely sampled by the the FIRST (Faint Images of the Radio Sky at Twenty-cm; Becker, White & Helfand, 1995) survey, with a flux limit of 1 mJy at 1.4 GHz. The sky area covered by both surveys is ∼8,800 square degrees. SDSS 1146+403 is detected in the radio with a flux of ∼13 mJy at 1.4 GHz, while VLBI observations yielded a flux of 15.5±0.8 and 8.6±0.4 mJy at 1.6 and 5 GHz, respectively (Frey et al. 2010). These fluxes correspond to a νL(ν) radio luminosity of ∼10^{44} erg s^{-1}. Comparing the radio and the optical flux we obtain a radio loudness of ∼100, calculated by assuming a flat radio spectrum (i.e. F(ν)∝ν^0) and calculating the rest frame 2500Å flux (which is not observed) by extrapolating the continuum to λ = 1350Å.

SDSS 1146+403 is included in the AllWISE Source Catalog, with clear detections in the two bands at lower wavelengths of the instrument, i.e. λ = 3.4μm and λ = 4.6μm. The source is not detected by the Large Area Telescope (LAT) onboard the Fermi satellite.

2.1 Swift observations

The large radio loudness of SDSS 1146+403 suggests a small viewing angle, and to confirm its blazar nature we observed the source with the Swift satellite (Gehrels et al. 2004). In fact the X-ray spectrum of FSRQs aimed towards us is particularly bright and hard, with an energy spectral index α_x ∼ 0.5 [F(ν)∝ν^{-0.5}] (see e.g. Ghisellini et al. 2010b, Wu et al. 2013).

The observations were performed between Jan. 16 and Jan 30 2013 (ObsIDs: 00049384001, 00049384002, 00049384003, 00049384004, 00049384005, 00049384007, 00049384008, 00049384009). The ObsID 00049384001 e 00049384009 did not generate spectra nor light–curves.

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 Swiftx software included in the package HEASoft v. 6.15 and analysed. The calibration database was updated on 12, 2013. We did not consider the data of the Burst Alert Telescope (BAT, Barthelmy et al. 2005), given the weak X–ray flux.

The total exposure on the XRT was ∼40 ks. The mean count rate was (1.74 ± 0.21) ×10^{-3}, resulting in 71 total counts. The low statistics, the fit with a power law model with Galactic absorption (N_H = 1.65 ×10^{20} cm^{-2}, Kalberla et al. 2005) was done by using the likelihood (Cash 1979). The output parameters of the model were a photon spectral index Γ_x = (α_x + 1) = 1.5 ± 0.3 and an integrated observed flux F_{0.3–10 keV} = (1.0 ± 0.12) ×10^{-13} erg cm^{-2} s^{-1}. The value of the likelihood was 54.93 for 63 dof. The X–ray data displayed in the SED (Fig. 2) has been re-binned to have 3σ in each bin.

UVOT observed the source only in the v filter. The total was 61.2 ks. The source was not detected, and can derive a 3σ upper limit τ > 22.46 mag. We expect, along the line of sight, some absorption due to the intervening matter. A rough estimate of the optical depth for the UVOT v filter for z = 5 gives τ ∼ 2 (F.

1 Data retrieved from: http://irsa.ipac.caltech.edu/
Using a larger efficiency would enhance the emission at high (rest frame UV) frequencies. Assuming that the disk emits the same flux, this implies a smaller black hole mass (see the discussion on this issue in Calderone et al. 2013).

Fig. 1 shows the data in the IR–optical band (as labelled) and three disc emission spectra calculated assuming the same luminosity and different $M_{BH}/M_\odot = 6 \times 10^9$ (red), $5 \times 10^9$ (blue) and $4 \times 10^9$ (green). Note that outside this range of masses, the model cannot fit satisfactorily the data.

3 OVERALL SPECTRAL ENERGY DISTRIBUTION

Fig. 2 shows the overall SED of SDSS 1146+403 together with the adopted models, as labelled. Data from WISE, GROND, Swift/XRT and Fermi/LAT are labelled. Green points are archival data taken from ASDC SED builder. The two optical photometric points receive some contribution from the emission line flux, besides the continuum. We show the optical–IR emission one would then require a larger black hole mass (see the discussion on this issue in Calderone et al. 2013).

Both models fit the X–radio data and are very similar in the radio band. Having the same black hole mass and accretion rate, they correspond to jets with a very different intrinsic power. The small $\Gamma$, relatively large $\theta_v$ solution implies a much less beamed emission, and therefore demands a greater intrinsic power. This leads us to prefer the more “economic” solution. Note that the models differ in the hard X–ray range, where the source could be detected by the NuSTAR satellite (sensitive up to ~80 keV; Harrison et al. 2013).

3.1 Comparison with Q0906+6930 and B2 1023+25

Fig. 3 shows the SED of 1146+403 compared with the SED of Q0906+6930 and B2 1023+25. These sources have approximately the same IR–optical spectrum, and also the X–ray spectra are remarkably similar. The main difference is in the source, located at a distance $R_{\text{diss}}$ from the black hole. The jet is viewed at an angle $\theta_v$ from the jet axis. The accretion disk component is accounted for, as well the infrared emission reprocessed by a dusty torus and the X-ray emission produced by a hot thermal corona sandwiching the accretion disc. We present two models. The first ($\Gamma = 13; \theta_v = 3^\circ$) is the best representation of the data assuming a set of parameters very similar to other powerful blazars (Ghisellini et al., 2010a; 2010b), while the second assumes $\Gamma = 6$ and $\theta_v = 12^\circ$. This latter choice corresponds to the model with the maximum viewing angle compatible with the data and a still reasonable bulk Lorentz factor. Tab. 1 reports the relevant parameters of the two models of SDSS 1146+403, together with the parameters for the other two blazars at $z > 5$.

**Figure 1.** Optical–UV SED of SDSS 1146+403 in the rest frame, together with models of standard accretion disc emission. Optical and UV data, including the SDSS spectrum, have been corrected for the extinction in our Galaxy. Data from WISE (AllWISE Source Catalog) and GROND, and the SDSS spectrum are labelled. Green points are archival data taken from ASDC SED builder. The two optical photometric points receive some contribution from the emission line flux, besides the continuum. We show the spectrum of three accretion disc models with the same luminosity and different $M_{BH}/M_\odot = 6 \times 10^9$ (red), $5 \times 10^9$ (blue) and $4 \times 10^9$ (green). Note that outside this range of masses, the model cannot fit satisfactorily the data.

**Figure 2.** SED of SDSS 1146+403 together with the adopted models, as labelled. Data from WISE, GROND, Swift/XRT and Fermi/LAT are labelled. Green points are archival data taken from ASDC SED builder. The two optical photometric points receive some contribution from the emission line flux, besides the continuum. We show the spectrum of three accretion disc models with the same luminosity and different $M_{BH}/M_\odot = 6 \times 10^9$ (red), $5 \times 10^9$ (blue) and $4 \times 10^9$ (green). Note that outside this range of masses, the model cannot fit satisfactorily the data.
The size of the region emitting the radio flux at ∼ GHz frequencies must be much larger (and therefore more external) than the X–ray region, since otherwise the flux would be self–absorbed. This is the reason why our one–zone model cannot reproduce the radio below a several tens of GHz. The smaller radio flux of SDSS 1146+403 could then be due to a jet bending between the X–ray and the radio regions. Assuming a constant Γ = 13, the radio deficit (factor ∼20) can be explained by a change in viewing angle from θv = 3◦ (corresponding to the X–ray production region of the jet) to θv = 6◦ (corresponding to the jet region producing the radio).

Alternatively, the jet could decelerate between the two regions maintaining the same viewing angle: in this case Γ must decrease by a factor 20^{1/4} ∼ 2.1. However, in this case, the deceleration should correspond to a relevant dissipation, in turn corresponding to some emission, which we do not see. It would be interesting to observe the source at high radio frequencies (100–300 GHz, rest frame), to see if the radio deficit remains the same or becomes smaller.

### Table 1

| Name         | z       | R_{diss} | M   | R_{BLR} | $P'_\gamma$ | $L_{\gamma}$ | $L_d/L_{Edd}$ | B   | θ_e | γ_b | $\gamma_{\max}$ | P_{\theta} | P_B | P_{\theta}/P_B | P_B/P_{\Gamma} |
|--------------|---------|----------|-----|---------|-------------|--------------|---------------|-----|-----|-----|----------------|------------|-----|----------------|----------------|
| 1146+430     | 5.005   | 900      | 5e9 | 1006    | 7e-3        | 100          | 0.15          | 1.4 | 13  | 3   | 230           | 3e3        | 3.7 | 10.3           | 0.05           | 15.1          |
| 1146+430     | 5.005   | 900      | 5e9 | 1006    | 0.8         | 100          | 0.15          | 1.5 | 6   | 12  | 50            | 3e3        | 75.9 | 2.3            | 4.6            | 741           |
| 0906+693     | 5.47    | 630      | 3e9 | 822     | 0.02        | 67.5         | 0.17          | 1.8 | 13  | 3   | 100           | 3e3        | 10.4 | 8.2            | 0.2            | 58            |
| 1023+25      | 5.3     | 504      | 2.8e9| 920     | 0.01        | 90           | 0.25          | 2.3 | 13  | 3   | 70            | 4e3        | 5    | 8.5            | 0.14           | 40.7          |

### Figure 3

Comparison between the SED of SDSS 1146+403 (red symbols) with B2 1023+25 (green symbols) and Q0906+693 (black symbols). The solid lines corresponds to the models whose parameters are listed in Tab. 1 (for 1146+403 we show the model with $\Gamma = 13$ and $\theta_v = 3^\circ$). The three sources are very similar in the IR–optical and X–rays, but SDSS 1146+403 is a factor ∼20 less luminous in the radio. The strong X–ray luminosity (with respect to the optical) and the hard X–ray spectra flag the presence of jet radiation beamed in the observer’s direction. The difference in the radio band could be due to a slight bend of the jet between the regions emitting X–rays (inner jet) and the radio (more external jet).

4 DISCUSSION AND CONCLUSIONS

In this letter we propose that the radio–loud, high redshift quasar SDSS 1146+403 is a blazar. If so, it is the third most distant blazar known up to now, with redshift $z = 5.005$, that corresponds to a cosmic age 1.1 billion years. Despite this young age, the black hole of SDSS 1146+403 managed to grow to 5 billion solar masses.

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 $\gamma$–ray band constrain the high energy component to peak in the MeV region of the spectrum. Therefore this source, along with the similar other powerful blazars, should have a relatively large hard X–ray emission.
flux and would have been an ideal target for hard X-ray instruments such as the focussing hard X-ray telescope NuStar (Harrison et al., 2013). The great sensitivity over its energy range [5–80 keV] would enable it to detect the hard X-ray spectrum of this source, even if it cannot directly observe the peak of the high energy hump.

It is possible to roughly estimate the number of these objects and their spatial density. The comoving density of heavy black holes at high redshifts of radio-loud sources has been studied by Volonteri et al. (2011), based on the 3 years BAT catalog 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 black holes heavier than $10^9 M_\odot$ 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 $2.63 \times 10^{-5}$ Gpc$^{-3}$ of blazars hosting an heavy black hole in the $5 < z < 6$ bin (see Fig. 15 in that paper).

SDSS J1146+403 was selected in the SDSS catalog covered by FIRST observations, and the common area of the sky of these two surveys is 8770 square degrees. It is the second source that can be classified as a blazars in this SDSS+FIRST survey (together with B2 1023+25). The comoving volume in the redshift bin $5 < z < 6$ is 380 Gpc$^3$. Therefore the number density of blazars in this redshift bin is $N_{BL} = 2 \times (40,000/8,770)/380 = 2.4 \times 10^{-2}$ Gpc$^{-3}$. Both B2 1023+25 and SDSS J1146+403 have black holes with $M > 10^9 M_\odot$. To find out the density of black holes in jetted sources heavier than one billion solar masses, we should consider that for each jet observed within a viewing angle $\theta_v = 1/\Gamma$, there exist another $2\Gamma^2$ sources pointing in other directions. So the number density of black holes with $5 < z < 6$, with a mass exceeding $10^9 M_\odot$, is $0.024 \times 2 \times 160(\Gamma/13)^2 = 8.1$ Gpc$^{-3}$. Multiplying by the comoving volume gives ~3,000 heavy black holes in jetted sources only.

As mentioned in the introduction, the finding of heavy and early black holes in sources with jets can severely challenge our understanding of black hole growth, especially if we associate the presence of the jet with a rapidly spinning black hole. A Kerr black hole is in fact more efficient to transform gravitational energy into radiation than a non spinning (radio-quiet) black hole. This lends support to the possibility of super–Eddington accretion (Volonteri & Silk 2014), and/or to the possibility that part of the gravitational energy of the accreting matter is not used to heat the disk, but to amplify the magnetic fields necessary to extract the rotational energy of the black hole (see e.g. Jolley & Kunzic 2008; Shankar et al. 2008, Ghisellini et al. 2013).

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