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Do high-redshift quasars have powerful jets?

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ABSTRACT

Double-lobed radio galaxies a few hundreds of kpc in extent, like Cygnus A, are common at redshifts of 1–2, arising from some 10 per cent of the most powerful active galactic nuclei (AGN). At higher redshifts, they are rare, with none larger than a few tens of kpc known above redshift $z \sim 4$. Recent studies of the redshift evolution of powerful jetted objects indicate that they may constitute a larger fraction of the AGN population above redshift 2 than that appears from a simple consideration of detected GHz radio sources. The radio band is misleading as the dramatic $(1 + z)^4$ boost in the energy density of the cosmic microwave background (CMB) causes inverse Compton scattering to dominate the energy losses of relativistic electrons in the extended lobes produced by jets, making them strong X-ray, rather than radio, sources. Here, we investigate limits to X-ray lobes around two distant quasars, ULAS J112001.48+064124.3 at $z = 7.1$ and SDSS J1030+0524 at $z = 6.3$, and find that powerful jets could be operating yet be currently undetectable. Jets may be instrumental in the rapid build-up of billion $M_\odot$ black hole at a rate that violates the Eddington limit.

Key words: black hole physics – X-rays: binaries.

1 INTRODUCTION

Extended X-ray emission produced by inverse Compton (IC) scattering of cosmic microwave background (CMB) photons in distant giant radio sources has been considered several times (Felten & Rees 1969; Schwartz 2002a; Celotti & Fabian 2004; Ghisellini et al. 2013a,b). Relativistic electrons with Lorentz factor $\Gamma \sim 10^3$ upscatter CMB photons into the soft-X-ray band observed around 1 keV. The boost factor in CMB energy density compensates for surface brightness dimming with redshift. The X-ray phase is also expected to even last longer than the radio phase (Fabian et al. 2009; Mocz, Fabian & Blundell 2011a). Many examples (e.g. Carilli et al. 2002; Scharf et al. 2003; Overzier et al. 2005; Blundell et al. 2006; Erlund et al. 2006; Laskar et al. 2010; Smail et al. 2012; Smail & Blundell 2013) of double-lobed sources simultaneously luminous in both radio and X-rays are known across a wide range in redshift up to $z \sim 4$. The highest redshift example of a >100 kpc scale double-lobed structure is 4C23.56 (Blundell & Fabian 2011) at $z = 2.5$. When IC losses are considered, the dearth of large radio galaxies at higher redshifts does not necessarily indicate a lack of high-redshift jetted sources (Mocz, Fabian & Blundell 2013; Ghisellini et al. 2014).

At $z > 7$, the energy density of the CMB is over 4000 times greater than at the present epoch and very likely far exceeds that of the magnetic field in any lobes produced by a jet, so making synchrotron radio emission weak and undetectable at GHz frequencies. Hard-X-ray emission detected from relativistically beamed jets by the Burst Alert Telescope (on board *Swift*) implies that the ratio of powerful radio-loud active galactic nuclei (AGN) to radio-quiet AGN strongly increases with redshift (Ghisellini et al. 2013a,b, 2014). The number density obtained when beaming corrections are accounted for nearly matches that of all massive dark matter haloes capable of hosting billion-solar-mass black holes above redshift 4 (Ghisellini et al. 2013a,b). It is therefore possible that X-ray-lobed sources produced by powerful jets exist, and could even be common, at high redshift. In other words, high-redshift quasars may have powerful jets.

To test whether powerful high-redshift quasars generate powerful jets, we searched for linearly extended, diametrically opposed X-ray lobes around archival X-ray images of two distant quasars, the most extreme object, ULAS J1120+0641 at $z = 7.1$, and SDSS J1030+0524 at $z = 6.3$. Both have relatively deep *XMM* exposures (Page et al. 2014 and Farrah et al. 2004, respectively). Schwartz (2002b) has previously searched for X-ray jets around

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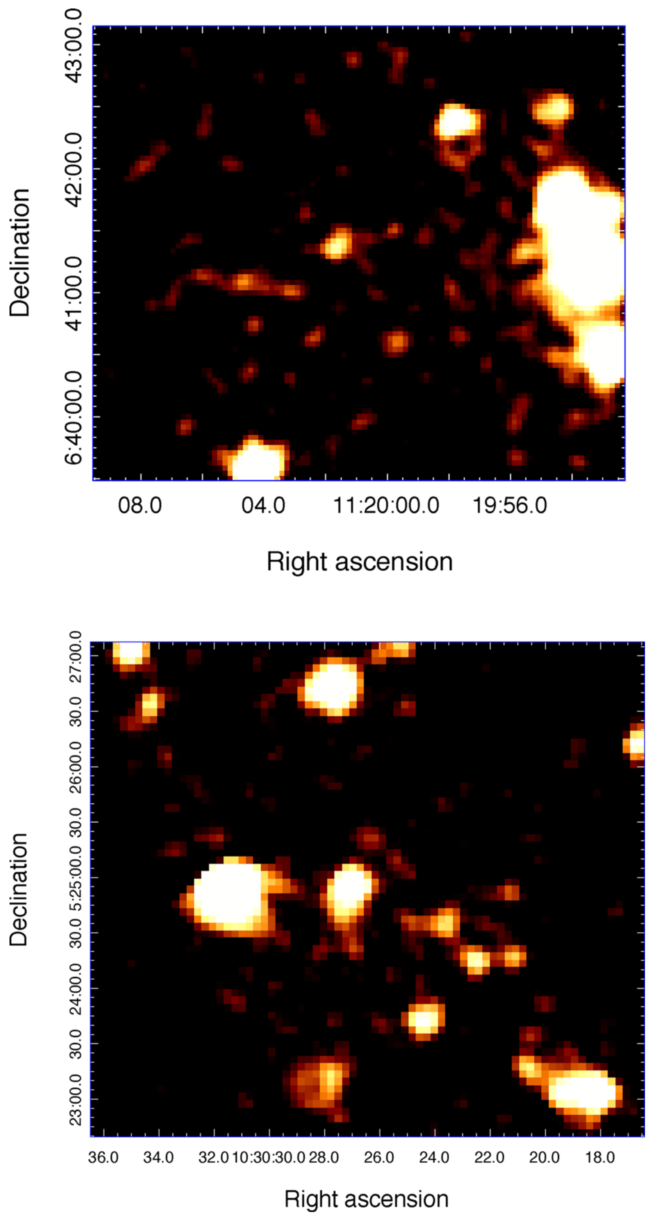

Figure 1. *XMM* images of ULAS J1120+0641 (z = 7.1, top) and SDSS J1030+0524 (z = 6.3, bottom). The energy band of both images is 0.3–1 keV.

three $z \sim 6$ quasars using short (∼10 ks) *Chandra* images without any conclusive result.

2 THE X-RAY IMAGES

2.1 ULAS J1120+0641

Neither the *Chandra* image (which is short, 16 ks) nor the *XMM–Newton* pn+MOS image data (Page et al. 2014, total exposure of 300 ks which on reanalysis gives 120 ks of useable, low-background exposure) show any significant linear structure around the quasar (Fig. 1). A linear structure which is ∼1 arcmin long (projected length of 318 kpc at z = 7.1, corresponding to a true length of >385 kpc if inclined at <60 deg to our line of sight) is seen about 1 arcmin to the WSW, centred on a weak point source. The structure either side of the weak source is at a statistically significant flux above the background (4.3σ), but we note smaller blobs (possibly sources) at the same surface brightness level and suspect that it may be due to source confusion. It is difficult to deduce a precise significance for any weak extended structure but note that in this and other *XMM* images we see no similar linear features. Where lines do appear, they correlate with chip gaps. The structure does not align with a chip gap or anything on the exposure map. The linear feature is present below about 1.5 keV and is best seen between 0.3 and 1 keV. We shall take this structure as representative of the upper limit of what is undetectable. No object consistent with high redshift is seen at the position of the weak point X-ray source in *HST* imaging of the field (Simpson et al., submitted).

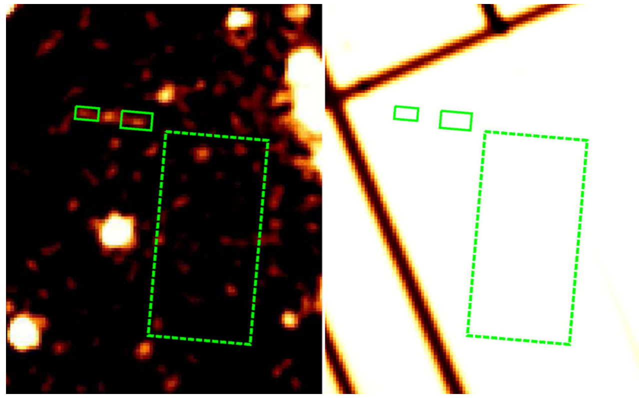

Figure 2. Left: 0.3–1.0 keV merged MOS and pn image showing the spectral extraction regions for the lobes (green boxes) and the background (blue box). Right: the same region files overlaid on the merged exposure map, showing no structures in the exposure maps that could have erroneously caused the linear lobe feature around the quasar.

In Fig. 2, we show the regions used for the source and background overlaid on the merged image and the merged exposure map. The merged exposure map contains no features that could have caused the observed lobe structure. For the 0.3–1 keV band, we find a total of 69 (48) counts for the pn+MOS (pn) in the two regions (arms) on either side of the weak source, shown as green boxes in Fig. 1. The background level estimated from the large region indicated by the dashed green box implies an expectation of 41.5 (26.5) counts in the source boxes. The arms therefore correspond to 27.5 (21.5) counts, or 4.3σ (4.2σ), above background, which is an observed flux of 2×10^{-16} erg cm^{-2} s^{-1} in the 0.3–1 keV band. Correcting the flux for Galactic absorption (hydrogen column density of 5×10^{20} cm^{-2}; Kalberla et al. 2005) gives an intrinsic 2–10 keV luminosity of 2.2×10^{44} erg s^{-1}. We henceforth use that value as our detection limit on large linear structures, such as X-ray lobes.

No radio emission has yet been detected from ULAS J1120+0641 (Momjian et al. 2014) or its near vicinity (analogously to the $z \sim 2$ AGN HDF130 that only has X-ray lobes; Fabian et al. 2009; Mocz et al. 2011a,b). The lack of radio emission in this z = 7.1 quasar is consistent with our modelling results if the magnetic field in the lobes is about 10 μG, which is about a factor of 5 below equipartition. Deeper lower frequency radio imaging could detect faint radio emission from any lobes, if present.

2.2 SDSS J1030+0524

Farrah et al. (2004) discuss SDSS J1030+0524 and its *XMM* data, which has about 75 ks of useable data. The X-ray image is shown in Fig. 1 (lower) and shows some structures close to the quasar which are most probably due to weak confused sources. We adopt the same upper limit to that for ULAS J1120+0641, given the similarities in *XMM* exposure time. The source was undetected in the radio band at 1.4 GHz by Petric et al. (2003). The arcmin size, double radio source one arcmin south of the quasar shown in their 1.4 GHz radio map is marginally coincident with several weak X-ray sources. No further information or identification has been made of that radio source.

3 MODELLING

The luminosity upper limit we have adopted is similar to that predicted by recent models for jetted lobe evolution (Mocz et al. 2013; Ghisellini et al. 2014). The properties of a jet powering a radio lobe at $z = 7.1$ are estimated using the analytic model developed in Mocz et al. (2013). The model treats the evolution of the hydrodynamics of the radio lobe and derives the synchrotron emission (in the radio) and the IC emission (in the X-rays) from it, also accounting for adiabatic expansion energy losses. We fix the magnetic field to 10 μG and use fiducial parameters for the injection spectrum and surrounding gas profile (set [A] in Mocz et al. (2011): the injection spectrum is given by a power-law index 2.14 and Lorentz factors ranging between 1 and 10^6; the surrounding density profile has a power-law index of 1.5). We assume each lobe has length 185 kpc so that the jet axis is at 60 deg to our line of sight and model the observed radio lobe at $z = 7.085$ with a (very powerful) jet power of $Q = 8 \times 10^{45}$ erg s^{-1} per lobe. The lobes each grow to 185 kpc in 1.4×10^7 yr. The observed X-ray power (1 keV) of a single lobe given by the model at this point in the evolution is 1.1×10^{44} erg s^{-1} (Fig. 3). The observed radio power (1.4 GHz) is estimated to be 1.8×10^{41} erg s^{-1}.

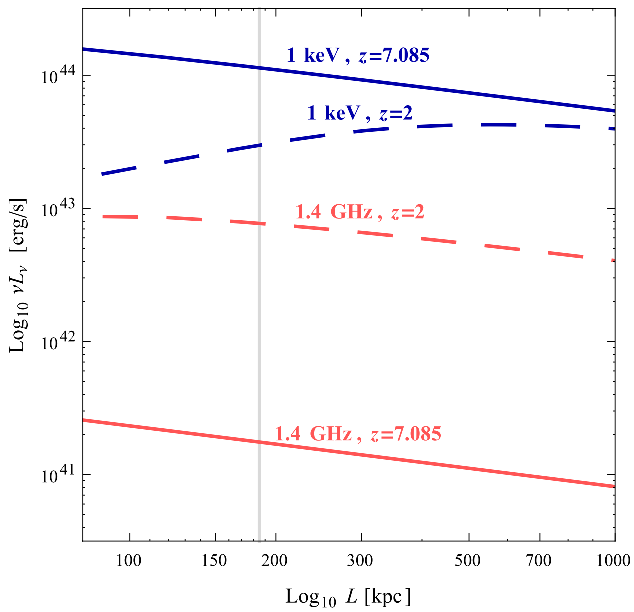

Figure 3. Modelled observed X-ray and radio powers versus length of a single radio lobe at $z = 7.085$ with jet power $Q \sim 2 \times 10^{46}$ erg s^{-1} shown as solid lines. A lobe is also modelled at $z = 2$ for comparison, and shown as dashed lines. At higher redshift, the energy density of the CMB is larger, resulting in a source that is brighter in its IC emission (X-ray) and lower in its synchrotron emission (radio) due to IC energy losses of the electrons. The length of each lobe is taken to be 185 kpc which assumes that it is oriented at 60 deg to our line of sight. Leptonic jets are assumed; if protons are present, the jets can carry 10 times more energy.

This thus requires a total jet power of 2×10^{46} erg s^{-1} acting for over 10^7 yr in order for each lobe to grow longer than 185 kpc. For an accretion efficiency of 0.1, the black hole will have grown by 4×10^7 M$_\odot$ in this jet outburst. A longer outburst leading to larger lobes, or several shorter outbursts would enable this process to account for much of the black hole mass. If the black hole is spinning rapidly then the accretion efficiency increases and the accretion rate reduces. However, this may be more than offset by a significant proton content to the jets which can increase the jet power 10-fold and make the black hole grow much faster.

4 DISCUSSION

We have shown that IC lobes produced by powerful jets powered by the central quasar could be currently undectable despite the fact that the jet power rivals that radiated by the quasar. This becomes more extreme if the jet contains protons as well as electrons. Jets could be the result of the extraction of rotational energy of the black hole (Blandford & Znajek 1977), but the accretion disc must amplify the magnetic field needed for the extraction of the black hole spin energy. This can correspond to the major energy release of the accretion process which, as widely assumed, powers the quasar. If substantial energy is extracted from the accretion disc magnetically, then the total power of the source could exceed the Eddington limit, a constraint which applies only to the power in photons (see discussion in Ghisellini et al. 2013a,b). A billion M$_\odot$ black hole can thereby grow from stellar mass by accretion before redshift 7.1.

The upper limit to any X-ray lobe of ULAS J1120+0641 (and SDSS J1030+0524) implies that the process of massive black hole growth at large redshift could include powerful jetted outflows. Much of the radiation is due to IC upscattering of CMB photons into the X-ray band. The enormous mechanical energy of jetted lobes would represent a formidable and fierce form of kinetic feedback on the surrounding gas (Fabian 2012). This could explain why the galaxy hosts of quasars at $z > 3$ are compact (Szomoru et al. 2013), and their group and cluster gas have more energy than is explainable by gravitational infall alone (Wu, Fabian & Nulsen 2000; McCarthy et al. 2012). Powerful jets are a considerable source of energy, magnetic fields and cosmic rays to the intergalactic medium[1] and may therefore play a role in reionization of the Universe at these early cosmic times. Our results suggest that the high-redshift sky could be criss-crossed by X-ray-emitting jets and lobes from growing massive black holes. Deeper X-ray imaging with *Chandra* and, in time, *Athena* can test this possibility.

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