Radio lobes and X-ray hotspots in the microquasar S26

Roberto Soria, Manfred W. Pakull, Jess W. Broderick, Stephane Corbel and Christian Motch

1 Mullard Space Science Laboratory, University College London, Holmbury St Mary, Surrey RH5 6NT
2 University of Strasbourg, CNRS UMR 7550, Observatoire Astronomique, 11 rue de l’Université, 67000 Strasbourg, France
3 School of Physics & Astronomy, University of Southampton, Southampton, Hampshire SO17 1B1
4 Université Paris 7 and Service d’Astrophysique, UMR AIM, CEA Saclay, F-91191 Gif sur Yvette, France

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ABSTRACT
We have studied the structure and energetics of the powerful microquasar/shock-ionized nebula S26 in NGC 7793, with particular focus on its radio and X-ray properties. Using the Australia Telescope Compact Array, we have resolved for the first time the radio lobe structure and mapped the spectral index of the radio cocoon. The steep spectral index of the radio lobes is consistent with optically-thin synchrotron emission; outside the lobes, the spectral index is flatter, suggesting an additional contribution from free–free emission, and perhaps ongoing ejections near the core. The radio core is not detected, while the X-ray core has a 0.3–8 keV luminosity ≈6 × 10^{36} \text{ erg s}^{-1}. The size of the radio cocoon matches that seen in the optical emission lines and diffuse soft X-ray emission. The total 5.5-GHz flux of cocoon and lobes is ≈2.1 mJy, which at the assumed distance of 3.9 Mpc corresponds to about three times the luminosity of Cas A. The total 9.0-GHz flux is ≈1.6 mJy. The X-ray hotspots (combined 0.3–8 keV luminosity ≈2 × 10^{37} \text{ erg s}^{-1}) are located ≈20 pc outwards of the radio hotspots (i.e. downstream along the jet direction), consistent with a different physical origin of X-ray and radio emission (thermal-plasma and synchrotron, respectively). The total particle energy in the bubble is ≈10^{53} \text{ erg}: from the observed radio flux, we estimate that only approximately a few times 10^{50} \text{ erg is stored in the relativistic electrons; the rest is stored in protons, nuclei and non-relativistic electrons. The X-ray-emitting component of the gas in the hotspots contains } \approx10^{51} \text{ erg, and } \approx10^{52} \text{ erg over the whole cocoon. We suggest that S26 provides a clue to understand how the ambient medium is heated by the mechanical power of a black hole near its Eddington accretion rate.}

Key words: black hole physics – ISM: bubbles – ISM: jets and outflows – galaxies: individual: NGC 7793 – radio continuum: ISM – X-rays: binaries.

1 INTRODUCTION

The basic physical model for radio lobes in Fanaroff–Riley type II (FR II) radio galaxies is based on a pair of relativistic, collimated jets emerging from the active black hole (BH). As the jet interacts with and is decelerated by the ambient (interstellar or intergalactic) medium, a reverse shock propagates inwards into the ejected plasma. After crossing the reverse shock, the jet material inflates a cocoon of hot gas, which is less dense but much overpressured with respect to the undisturbed medium. Thus, the cocoon expands supersonically, driving a forward shock (bow shock) into the ambient medium (Blandford & Rees 1974; Scheuer 1974; Begelman, Blandford & Rees 1984; Rawlings & Saunders 1991; Kaiser & Alexander 1997). The cocoon and lobes are the main sources of optically-thin (steep spectrum) synchrotron radio emission, while we expect optically-thick (flat-spectrum) radio emission from the jet near the core. A radio- and sometimes X-ray-luminous hotspot is usually found at the reverse shock, at the end of the jet. This is where most of the bulk kinetic energy of the jet is transferred to thermal ions and to a non-thermal population of ultrarelativistic electrons, which cool via synchrotron and synchrotron self-Compton emission. Non-thermal X-ray emission at the hotspot position may be due to synchrotron and synchrotron self-Compton emission. Optically-thin thermal plasma X-ray emission may come instead from the hot, shocked ambient gas between the reverse shock and the bow shock; in this case, the peak of the thermal X-ray emission will appear just in front of the radio hotspots.

There is a scale invariance between the jet emission processes in microquasars (powered by stellar-mass BHs) and in active galactic
nuclei (AGNs)/quasars (powered by supermassive BHs). There is also at least one important difference: microquasars are mostly located in a relatively low-pressure medium as compared to the medium around AGNs, when scaling of the jet thrust is taken into account (Heinz 2002). As a consequence, we expect to see fewer, dimmer cocoons and radio lobes in microquasars than in the most powerful AGNs and quasars; however, the linear sizes of those microquasar cocoons and jets can be up to 1000 times larger than in radio galaxies, scaled to their respective BH masses. There is also evidence that some microquasars are located inside low-density cavities, compared with the undisturbed interstellar medium (Hao & Zhang 2009).

So far, our knowledge of the interaction of microquasar jets with the interstellar medium has largely relied on the Galactic microquasar SS 433 (Fabrika 2004) and its surrounding synchrotron-emitting nebula W50 (size \(\sim 100 \times 50 \) pc). A mildly relativistic \((v_{\text{jet}} = 0.27c)\), precessing jet acts as a sprinkler that inflates ‘ear-like’ lobe structures, protruding from the more spherical W50 nebula. Most of the jet power \((\sim 10^{39} \text{ erg s}^{-1})\) is dissipated in the lobes (Begelman et al. 1980). Faint evidence of the interaction of relativistic jets with the interstellar medium has been found in a few other less-powerful Galactic microquasars, for example, Cyg X-1 (Gallo et al. 2005), GRS 1915+105 (Kaiser et al. 2004), XTE J1550–564 (Corbel et al. 2002), H1743–322 (Corbel et al. 2005) and around the neutron star Sco X-1 (Fomalont, Geldzahler & Bradshaw 2001). On a larger scale, huge \((\text{size} \gtrsim 100 \text{ pc})\) ionized nebulae have been found around several ultraluminous X-ray sources (ULXs) in nearby galaxies (Pakull & Mirioni 2002; Roberts et al. 2003; Pakull, Gris & Motch 2006; Feng & Kaaret 2008; Gris et al. 2008; Pakull & Gris & Gris 2008). Such nebulae emit optical lines typical of shock-ionized gas, and in a few cases, synchrotron radio emission (Müller, Mushotzky & Neff 2005; Soria et al. 2006; Lang et al. 2007). The derived ages \((\text{greater than or equal to a few times} 10^{5} \text{ yr})\) and energy content \((\sim 10^{52}–10^{53} \text{ erg})\) are too large for ordinary supernova remnants and suggest jet/wind inflation with a mechanical power \((\sim 10^{39}–10^{40} \text{ erg s}^{-1})\), comparable with the X-ray luminosities (Pakull et al. 2006). However, no direct X-ray or radio evidence of a collimated jet has been found in ULX bubbles so far. On the other hand, X-ray-luminous sources may be only a subset of non-nuclear BHs at very high mass accretion rates. Pakull & Gris (2008) proposed that ionized bubbles might also be found associated with BHs that appear X-ray faint, either because their radiative emission is collimated away from our line of sight or because they are transients and currently in a low/off accretion state or because they channel most of their accretion power into a jet even at near-Eddington mass-accretion rates.

2 THE MICROQUASAR S26 IN NGC 7793

A spectacular example of such systems was recently discovered (Pakull, Soria & Motch 2010, hereinafter PSM10) in the outskirts of the Sculptor galaxy NGC 7793 (Fig. 1), at a distance of 3.9 Mpc (Karachentsev et al. 2003). The radio/optical nebula S26 was originally classified as a supernova remnant candidate (Blair & Long 1997); the high \([\text{S} \text{II}]_{\lambda} 6716, 6732/\text{Hz}\) flux ratio indicates the presence of shock-ionized gas. The optical radial velocity of S26 agrees with that of NGC 7793, ruling out a chance superposition of a background AGN. A radio spectral index consistent with optically-thin synchrotron emission was reported by Pannuti et al. (2002) and the emitting region appeared clearly extended and elongated. However, the spatial resolution was too low to reveal details of its internal structure. A faint X-ray source was discovered to be associated with S26 in ROSAT observations (Read & Pietsch 1999), but it was unresolved. Using Chandra data, Pakull & Gris (2008) discovered that the X-ray emission is resolved into three sources that are perfectly aligned and match the extent of the major-axis of the radio and optical nebulae. Those sources have been interpreted as the core (at the X-ray binary position) and the X-ray hotspots (where the jet interacts with the ambient medium).

From optical spectroscopic observations, PSM10 determined the expansion velocity, density and temperature of the line-emitting gas in the bubble and discovered that the mechanical power of the central BH is approximately a few times \(10^{40} \text{ erg s}^{-1}\); this suggests accretion rates similar to those required for the most luminous ULXs. PSM10 showed that the jet power is orders of magnitude higher than both the X-ray luminosity and the value one would derive from the radio luminosity; they argued that most of the jet power is transferred to non-relativistic protons and nuclei rather than non-thermal relativistic electrons.

In this paper, we present the initial results of our radio study, showing for the first time the resolved lobe structure and measuring the spectral index variations across the source. We discuss the origin of the radio emission and the implied jet power. We compare the radio, X-ray and optical maps of the nebula, determining the positions of the radio and X-ray hotspots and of the core, and we provide a more detailed spectral analysis and interpretation of the X-ray properties. We then summarize the energy budget of this system, quantifying the fraction of energy stored in relativistic electrons and in the X-ray-emitting gas.

3 OBSERVATIONS

3.1 Radio observations

We observed S26 on 2009 August 6 and 7 with the Australia Telescope Compact Array (ATCA). Simultaneous 5.5- and 9-GHz observations were carried out with the Compact Array Broadband Backend (CABB); the bandwidth at each frequency is about 2 GHz. The array configuration was 6D, with minimum and maximum baselines of 77 and 5878 m, respectively. The total integration time on-source was 13.3 h; the data for antenna 6 at 9 GHz were lost during part of the second observing session due to
technical problems. B1934−638 was used as the primary calibrator, while our secondary calibrator was B2357−318.

We reduced and imaged the data with \textsc{miriad} (Sault, Teuben & Wright 1995). After flagging bad data, the effective frequencies of the two bands are 5.48 and 9.02 GHz. We tried different values of Briggs’ robust weighting parameter (Briggs 1995); we found that a value of 0.0 provides a good balance between sidelobe suppression and sensitivity at both frequencies. Because of the wide bandwidths, we used the multifrequency deconvolution algorithm \textsc{mfclean} (Sault & Wieringa 1994). The cleaned, primary-beam-corrected images are shown in Fig. 2; the angular resolutions are $3.54 \times 1.38$ arcsec$^2$ (position angle 1.1) and $2.67 \times 1.08$ arcsec$^2$ (position angle 6.8) at 5.48 and 9.02 GHz, respectively. In the vicinity of the microquasar, the rms noise levels are 8.5 mJy beam$^{-1}$ (5.48 GHz) and 13.5 mJy beam$^{-1}$ (9.02 GHz). We estimate that the internal calibration uncertainty is $\sim 2$ per cent at both frequencies.

We also tapered the 9.02-GHz data so that the resolution and beam position angle matched those of the 5.48-GHz data. We created a two-point spectral index map (Fig. 3), where the sign of the index is defined, such that the specific flux $S_\nu \sim \nu^\alpha$. For the tapered 9.02-GHz data, we found that a robust weighting parameter of 0.5 provides the best compromise between residual sidelobe contamination and sensitivity to the low surface brightness extended emission that is clearly visible in the 5.5-GHz map.

### 3.2 X-ray observations

NGC 7793 was observed with \textit{Chandra}/ACIS-S3 on 2003 September 6 (Obs ID 3954). The live time was 48.9 ks. We retrieved the data from the public archives (processed with ASCIIVER = 7.6.8), and analysed them with standard imaging and spectroscopic tools, such as \textsc{psfextract} in the data analysis system \textsc{ciao} Version 4.0 (Fruscione et al. 2006). We modelled the X-ray spectra with \textsc{xspec} Version 12.0 (Arnaud 1996). Luckily, the roll angle of the \textit{Chandra} observation was such that S26 was located rather close to the S3 aimpoint (less than 1 arcmin away), giving us a narrower point spread function.

### 4 MAIN RESULTS

#### 4.1 Radio results

The most important new result of our ATCA study is that we have resolved the spatial structure of the radio-emitting nebula. Most of the emission comes from two radio hotspots and surrounding lobes, with a fainter but clearly identified cocoon encompassing them (Fig. 2, top panel). This is the textbook structure (e.g. Begelman et al. 1984) of FR II powerful radio galaxies (e.g. Cygnus A: Carilli & Barthel 1996; Wilson, Smith & Young 2006). The radio structure is aligned with the jet axis suggested by the three X-ray sources, confirming this interpretation. The position of the northern radio hotspot is RA $= 23^h 57^m 59^s 58$, Dec. $= -32^\circ 33' 13.6''$ (with an uncertainty of $\approx 0.2'$). The position of the southern hotspot is RA $= 23^h 58^m 00^s 15.0$, Dec. $= -32^\circ 33' 25.0''$. Thus, the projected distance between the radio hotspots is (13.5 $\pm 0.3$) $\approx 250$ pc. We interpret the radio hotspots as the reverse shocks (Mach discs) at the ends of the jets.

At 5.5 GHz, the peak intensity in the southern lobe is $\approx 0.37$ mJy beam$^{-1}$; in the northern lobe, $\approx 0.21$ mJy beam$^{-1}$; the total flux in the lobes and cocoon is $\approx 2.1$ mJy (Table 1), that is, approximately three times the luminosity of Cas A. From the untapered map at 9 GHz, we obtain a peak intensity in the southern lobe $\approx 0.19$ mJy beam$^{-1}$; in the northern lobe, $\approx 0.11$ mJy beam$^{-1}$. The total flux at 9 GHz is $\approx 1.6$ mJy (Table 1). The spectral index in the lobes is, on average, $\approx -0.7$ to $-0.6$; it appears to be flatter ($\approx -0.4$ to 0) across most of the cocoon and inverted ($\approx 0$ to 0.4) at the base of the jets, on either side of the X-ray/optical core (Fig. 3). We...
estimate a 1σ uncertainty for α of ≈0.12 near the southern radio hotspot, ≈0.19 near the northern radio hotspot and ≈0.5–0.6 in the rest of the cocoon, where the emission is much fainter. Thus, the existence of a complex spatial structure for the spectral index is at this stage still an intriguing speculation that has to be tested with deeper observations.

4.2 X-ray results

The key feature of this system is the aligned triplet of point-like sources (Figs 4 and 5), which we interpret as the X-ray core and hotspots (Pakull & Grisê 2008). The X-ray core is located at RA = 23h57m59.94, Dec = −32°33′20.9″ (with an uncertainty of ≈0.2″). It has a hard spectrum (power-law photon index Γ = 1.4 ± 0.6), consistent with a BH in the low/hard state (Remillard & McClintock 2006), and an emitted luminosity $L_{\text{0.3-8}} \approx 6 \times 10^{36} \text{erg s}^{-1}$ (Table 2 and Fig. 6). The X-ray core coincides, within the astrometric uncertainties, with a point-like optical source with He II $\lambda$4686 emission (Fig. 5). The 90 per cent uncertainty circle of the ACIS-S3 absolute position has a radius of 0.4 arcsec,¹ and the uncertainty of the optical images is ≈0.3 arcsec.

The two hotspots have a much softer spectrum (Figs 4 and 6) and are well fitted (Table 3) by a two-component Raymond-Smith thermal

¹http://cxc.harvard.edu/cal/ASPECT/celmon/
plasma model (Raymond & Smith 1977) with $kT_1 \approx 0.3$ keV and $kT_2 \approx 0.9$ keV, and negligible intrinsic absorption (Cash statistics $= 10.4$ over 13 d.o.f. for solar abundances and 9.6 over 13 d.o.f. for one-fourth solar abundances). The emitted X-ray luminosities are $L_{0.3-8} \approx 5 \times 10^{38}$ erg s$^{-1}$ and $L_{0.3-8} \approx 11 \times 10^{38}$ erg s$^{-1}$ for the northern and southern hotspot, respectively (similar to the ratio of radio luminosities). In general, a choice of low metal abundances gives better fits than solar abundances, but the signal-to-noise ratio is not high enough to constrain this parameter. Other more complex thermal plasma models, such as mekal, vmekal, equil and nei, also give similar sets of best-fitting parameters; they all require at least two temperature components. However, the sedov thermal plasma model (Borkowski, Lyerly & Reynolds 2001) gives a good fit (Cash statistics $= 11.9$ over 15 d.o.f. for one-fourth solar abundances) with only one temperature component at $kT \approx 0.52$ keV (Table 4); the ionization age ($\tau$ parameter) of the sedov model is consistent with the characteristic age multiplied by the electron density in the S26 bubble. Given the small number of counts in the Chandra spectrum, none of the more complex thermal-plasma models can provide an improvement over the simpler raymond-smith model. Simple or broken power-law models do not give acceptable fits (Cash statistics $= 25.5$ over 15 d.o.f.), moreover, they would require an unphysically steep slope ($\Gamma \approx 6$) combined with high intrinsic column densities ($N_H \approx 5 \times 10^{22}$ cm$^{-2}$). We conclude that the hotspot spectra are not dominated by synchrotron or synchrotron self-Compton emission. We interpret them as optically-thin thermal plasma emission from hot, shocked gas, probably located between the reverse and forward shocks. The radius of the X-ray hotspots is $< 1$ arcsec. From the combined volume of the two hotspots and their emission measures (Table 3), we estimate a hot gas density $\gtrsim 1$ cm$^{-3}$ and a mass $\sim 10^{36}$ g (see also PSM10).

We also find faint X-ray emission projected over the surface of the cocoon (Fig. 5), with slightly softer colours than the hotspots; however, the number of detected counts is too low for detailed temperature comparisons. A single-temperature bremsstrahlung fit suggests $kT = 0.5 \pm 0.1$ keV (Table 5 and Fig. 7). It is also impossible to determine at this stage whether the X-ray-emitting
Alternative spectral models for the combined hotspot X-ray emission. A single-temperature wabs\textsubscript{Gal}*wabs*ray model does not produce acceptable fits. However, a single-temperature wabs\textsubscript{Gal}*wabs*sedov model results in a fit as good as those with two-temperature raymond-smith models (Table 3). Errors are 90 per cent confidence level for one interesting parameter.

| Parameter | Value |
|-----------|-------|
| $N_{\text{H, Gal}}$ | $1.2 \times 10^{20}$ cm$^{-2}$ (fixed) |
| $N_{\text{H}}$ | $<1.0 \times 10^{21}$ cm$^{-2}$ |
| $Z$ | $1$ (fixed) |
| $kT_1$ | $0.26 \pm 0.08$ keV |
| $N_1$ | $(2.3^{+0.9}_{-0.6}) \times 10^{-6}$ |
| $kT_2$ | $0.96^{+0.31}_{-0.17}$ keV |
| $N_2$ | $(1.9^{+0.7}_{-0.7}) \times 10^{-6}$ |
| $f_{0.3-8}$ | $(8.8^{+0.9}_{-0.9}) \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ |
| $L_{0.3-8}$ | $(1.7^{+1.2}_{-0.3}) \times 10^{37}$ erg s$^{-1}$ |
| EM (0.26 keV) | $(4.2^{+5.3}_{-1.1}) \times 10^{59}$ cm$^{-3}$ |
| EM (0.96 keV) | $(3.5^{+1.2}_{-1.0}) \times 10^{59}$ cm$^{-3}$ |
| C-statistic | 10.35 (13 d.o.f.) |

Table 4. Alternative spectral models for the combined hotspot X-ray emission. A single-temperature wabs\textsubscript{Gal}*wabs*ray model does not produce acceptable fits. However, a single-temperature wabs\textsubscript{Gal}*wabs*sedov model results in a fit as good as those with two-temperature raymond-smith models (Table 3). Errors are 90 per cent confidence level for one interesting parameter.

| Parameter | Value |
|-----------|-------|
| $N_{\text{H, Gal}}$ | $1.2 \times 10^{20}$ cm$^{-2}$ (fixed) |
| $N_{\text{H}}$ | $<2.5 \times 10^{21}$ cm$^{-2}$ |
| $Z$ | $0.25$ (fixed) |
| $kT_1$ | $0.78^{+0.07}_{-0.06}$ keV |
| $N_1$ | $(8.4^{+1.4}_{-1.4}) \times 10^{-6}$ |
| C-statistic | 28.9 (15 d.o.f.) |

Table 5. Best-fitting spectral parameters for the X-ray emission from the cocoon (not including the hotspots). The xspec models are wabs\textsubscript{Gal}*ray and wabs\textsubscript{Gal}*bremss. Adding intrinsic absorption does not improve the fit. Errors are 90 per cent confidence level for one interesting parameter.

| Parameter | Value |
|-----------|-------|
| $N_{\text{H, Gal}}$ | $1.2 \times 10^{20}$ cm$^{-2}$ (fixed) |
| $Z$ | $0.25$ (fixed) |
| $kT_1$ | $0.29 \pm 0.13$ keV |
| $N_1$ | $(3.9^{+1.2}_{-1.2}) \times 10^{-6}$ |
| $kT_2$ | $0.90^{+0.16}_{-0.16}$ keV |
| $N_2$ | $(4.9^{+2.0}_{-1.9}) \times 10^{-6}$ |
| $f_{0.3-8}$ | $(9.1^{+0.9}_{-0.9}) \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ |
| $L_{0.3-8}$ | $(1.8^{+1.2}_{-0.3}) \times 10^{37}$ erg s$^{-1}$ |
| EM (0.26 keV) | $(13.3^{+2.2}_{-2.6}) \times 10^{59}$ cm$^{-3}$ |
| EM (0.96 keV) | $(8.9^{+6.7}_{-3.5}) \times 10^{59}$ cm$^{-3}$ |
| C-statistic | 9.55 (13 d.o.f.) |
supernova. Based on the clear radio and X-ray evidence for a collimated jet pair (lobes, hotspots), PSM10 showed that such a large amount of energy has been supplied by the BH over the lifetime of the bubble (characteristic age $\approx 2 \times 10^8$ yr). The core is seen as a faint point-like X-ray source, consistent with a stellar-mass BH in the low/hard state, and a point-like optical source, consistent with an OB donor star (possibly a Wolf–Rayet; PSM10). It is undetected in the radio bands, to a $3\sigma$ upper limit $\approx 0.03$ mJy. This is unsurprising: if the BH lies in the Fundamental Plane (Merloni, Heinz & Di Matteo 2003; Körning, Falcke & Corbel 2006) with a mass $\sim 10 M_\odot$, we expect a core radio flux $\sim 0.01 \mu$Jy ($\nu L_\nu \sim 10^{38}$ erg s$^{-1}$), like from a common-or-garden low/hard-state microquasar at a distance of $3.9$ Mpc. On the other hand, the impact of this BH on to the surrounding interstellar medium is all but common. The simplest explanation is that the core is currently in a low/hard state, three or four orders of magnitude fainter than its long-term average power. In that same canonical state, the steady jet power $P \propto \dot{E}_{\text{acc}}^{3/5}$ (Fender, Gallo & Jonker 2003; Fender, Belloni & Gallo 2004; Malzac, Merloni & Fabian 2004). The normalization of this relation has an uncertainty of almost two orders of magnitude, but is constrained enough to suggest $10^{36} \lesssim P \lesssim 10^{38}$ erg s$^{-1}$, also much lower than the inferred long-term average. However, there may be alternative explanations for the apparent faintness of the core. Perhaps the observed X-ray luminosity is a severe underestimate of the true X-ray luminosity, if most of the direct emission is absorbed and/or beamed away from our line of sight (as it has been suggested for SS 433: Medvedev & Fabrika 2010) and we are only seeing a scattered component or perhaps the system is not in the canonical low/hard state, but in some other unclassified state with $P \propto L_X$.

The faint core is in stark contrast with the large, bright nebula, visible in all bands with a similar size and shape (Fig. 5), and a conservatively estimated volume $\approx 10^6$ cm$^{-3}$, assuming a prolate spheroid with a major-axis $\approx 280$ pc and minor-axis $\approx 130$ pc (based on the projected distance between the hotspots along the major-axis and the width of the radio nebula at 5.5 GHz in the transverse direction). In fact, H$\alpha$ images (PSM10) may suggest an even larger size, $\approx 340 \times 170$ pc. Thus, the volume-averaged shell radius $R_s \approx 100$ pc. Its characteristic size is an order of magnitude larger than the jet driven bubble around Cyg X-1, which has an estimated jet power $\sim 10^{37}$ erg s$^{-1}$ (Russell et al. 2007). It is a factor of 2 larger (allowing for distance uncertainties) than the radius of the SS433/W50 nebula, with an estimated jet power $\sim 10^{39}$ erg s$^{-1}$ (Marshall, Canizares & Schulz 2002; Fabrika 2004; Medvedev & Fabrika 2010).

PSM10 determined a mechanical power $P \approx 5 \times 10^{39}$ erg s$^{-1}$ for S26, using the well-known self-similar solution to the conservation of mass, momentum and energy equations (equations 17–22 in Weaver, McCray & Castor 1977), in which the radius of the swept-up shell $R_s \approx 0.76 \rho_s^{-0.15} \rho_0^{-0.15}$. They measured the expansion velocity from the half-width at zero-intensity of the optical emission lines ($v \approx 250$ km s$^{-1}$) and from shock-ionization models of the He II $\lambda 4686$/H$\beta$ flux ratio ($v \approx 275$ km s$^{-1}$). This implies a characteristic age $t = (3R_s)/(5v_{\text{obs}}) \approx 2 \times 10^5$ yr. The hydrogen number density of the interstellar medium into which the bubble expands was estimated as $n_h \approx 0.7$ cm$^{-3}$ (PSM10), from a comparison of the observed H$\alpha$ emission with the intensity of a fully radiative shock (Dopita & Sutherland 1996; Pakull et al. 2006); this corresponds to a mass density $\rho_0 \approx \mu n_h m_p \approx 1.6 \times 10^{-4}$ g cm$^{-3}$ (taking the mean atomic weight $\mu = 1.38$). The swept-up mass in the expanding shell is $(4\pi/3)\rho_v R_s^3 \approx 2 \times 10^{18}$ g, carrying a kinetic energy $\approx (15/77)P_t \approx 6 \times 10^{32}$ erg. The energy content of the thermal gas between the reverse shock and the swept-up shell is $E = (\dot{S}/11)P_t \approx 10^{35}$ erg.

5 DISCUSSION

5.1 Energetics of the bubble

We have presented radio and X-ray results from our multiband study of a powerful non-nuclear BH in NGC 7793 and of its surrounding shock-ionized cocoon (see PSM10 for a discussion of the evidence for shock-ionization from the optical emission lines). The system was originally classified as a supernova remnant (Blair & Long 1997). In that scenario, Asvarov (2006) showed that an input energy $\approx 5 \times 10^{52}$ erg was required to explain its size and radio luminosity, well beyond the energy that can be supplied by an individual

![Figure 7](https://academic.oup.com/mnras/article-abstract/409/2/541/1036379/57308)

**Figure 7.** *Chandra* ACIS spectrum of the cocoon emission, fitted with a $\approx 0.5$ keV bremsstrahlung model. See Table 5 for the best-fitting parameters.

![Figure 8](https://academic.oup.com/mnras/article-abstract/409/2/541/1036379/57308)

**Figure 8.** Close-up view of the southern lobe: true-colour image in the B, V, R bands taken by Dr. Jifeng Liu with the Baade Magellan telescope on 2009 August 28 (exposure time: 200 s per filter). The ATCA 9.02-GHz intensity contours are overplotted in green; the red circles mark the position of the X-ray core and southern hotspot. The point-like optical core has a brightness $B \approx 23$ mag, $M_B \approx -5$ mag (PSM10).
The only shock-ionized nebulae of comparable size and energy content in the local universe are those around ULXs such as Holmberg IX X-1, NGC 1313 X-2 and IC 342 X-1 (Pakull & Mirioni 2002; Ramsey et al. 2006; Feng & Kaaret 2008; Pakull & Grisé 2008). One difference is that, unlike all previously known ULX bubbles, S26 has clear evidence of collimated jets. We do not know the relative distribution of mechanical power between the collimated jets and perhaps a more spherically symmetric wind (e.g., an accretion disc wind); however, the elongated structure of the nebula and the presence of bright lobes and hotspots suggests that the jet carries most of the power. Another difference is that in ULX bubbles, the central BH is (by definition) X-ray luminous, with an apparent X-ray luminosity \( \sim 10^{38} \, \text{erg s}^{-1} \), similar to the mechanical power. S26 may be an example of a ULX bubble, where the central BH is currently in a low and/or jet-dominated state. In that respect, S26 is analogous to (but with two orders of magnitude more energetic than) the shock-ionized bubble around the very massive, but only moderately luminous non-nuclear BH IC 10 X-1 (Prestwich et al. 2007).

5.2 Synchrotron and thermal plasma emission

The detection of a radio cocoon with bright radio hotspots shows that some of the input mechanical power goes into synchrotron-emitting, relativistic electrons. As expected, the radio spectrum is steep in the lobes and flat or inverted near the position of the core (Fig. 3); this may be evidence of recent or continuing ejection activity (although the core itself is undetected in the radio). In addition, there is radio emission from the cocoon region outside the lobes, with a specific flux \( \approx 0.7 \, \text{mJy at 5.5 GHz} \). There is circumstantial evidence that this emission has a rather flat spectrum, certainly flatter than in the lobes (Fig. 3). This is difficult to reconcile with a scenario where the synchrotron-emitting electrons in the whole cocoon are backflowing from the lobes. In that case, the spectral index in the rest of the cocoon would be even steeper - as we see, for example, in Cygnus A (Carilli & Barthel 1996). We suggest that the extended radio emission in the cocoon outside the lobes may have a significant contribution from (flat-spectrum) free–free emission, from the same thermal gas responsible for the optical recombination lines. For the characteristic temperature \( T_{\text{H\beta}} \) and free–free radio emissivity \( \eta_{\text{H\beta}} / J_{5000} \approx 2 \times 10^{-10} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Jy}^{-1} \) (Caplan & Deharveng 1986, their appendix A). The \( \text{H\beta} \) luminosity of S26 is \( \approx 10^{38} \, \text{erg s}^{-1} \) (PSM10); thus, we expect a free–free radio flux \( \approx 0.3 \, \text{mJy at 5.5 GHz} \). This is negligible in the lobes, compared with the synchrotron component, but may be significant in the region outside the lobes, and may explain the rather flat spectral index there.

What fraction of the mechanical power is transferred to relativistic electrons? If we combine the self-similar model of cocoon expansion with the standard synchrotron emissivity, in the minimum-energy assumption, approximating a spectral index \( \alpha = -0.7 \), we obtain (Appendix A):

\[
S_{\nu} \approx 82 \left(1 + k\right)^{-1} \eta_{0.75}^{1.54} T_{\nu}^{3.13} \frac{d_{1}^{-2}}{t_{5}^{2}} \, \text{mJy},
\]

where \( \eta \) is the fraction of the total energy density contained in all relativistic species (electrons, protons and nuclei) plus magnetic field, \( (1 + k)^{-1} \) is the fraction of relativistic particle energy carried by the synchrotron-emitting electrons alone, \( T_{\nu} \) is the jet power in units of \( 10^{39} \, \text{erg s}^{-1} \), \( t_{5} \) is the source age in units of \( 10^{5} \) yr, \( n_{1} \) is the interstellar number density in \( \text{cm}^{-3} \), \( d_{1} \) is the source distance in Mpc and \( v_{5} \) is the observed frequency in units of 5 GHz. A few times higher specific flux is expected, if we assume \( \alpha = -0.5 \) (Appendix A).

If we assume that all the jet power is transferred to the relativistic electrons (i.e. if we put \( k = 0 \) and \( \eta = 1 \)), Equation (1) grossly overestimates the radio emission, for the measured jet power and distance of S26. (Conversely, the observed radio flux would lead us to underestimate the jet power if we do not know it independently.) This tells us that \( (1 + k)^{-1} \times \eta \approx 10^{-3} \). We cannot separately determine \( k \) and \( \eta \) from this simple model, but for plausible values of \( k \sim 10–100 \) found in cosmic rays, we estimate that the fraction \( (1 + k)^{-1} \times \eta \) of the total injected mechanical power carried by the relativistic electrons is approximately a few times \( 10^{-3} \). The rest of the energy is given to protons, nuclei and non-relativistic electrons, and is used for heating and inflating the bubble, accelerating the shell of swept-up interstellar medium to the expansion speed \( \approx 250 \, \text{km s}^{-1} \).

The X-ray emission from the hotspots and cocoon provides another clue to understand the energy budget. In radio galaxies, X-ray hotspots are usually interpreted either as direct synchrotron or synchrotron self-Compton emission (Harris & Krawczynski 2002; Hardcastle et al. 2004), from the same population of electrons responsible for the radio hotspots, which are accelerated at the reverse shock. For S26, we estimate from Chandra a specific flux \( \approx 10^{-14} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{keV}^{-1} \) at 1 keV from both hotspots, corresponding to \( \approx 4 \times 10^{-32} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \). The combined radio emission from the radio hotspots is \( \approx 1 \, \text{mJy} \). To sum up, we cannot yet rule out the possibility that some of the input mechanical power goes into synchrotron emission. However, the X-ray spectrum tells a different story. Its shape and slope are not consistent with either synchrotron or inverse-Compton power-law models, even accounting for the low number of counts. We showed (Section 4 and Fig. 6) that the X-ray emission from the hotspots, with its peak at \( \approx 0.6–0.9 \, \text{keV} \) and its sharp drop above \( \approx 1 \, \text{keV} \), is most likely due to hot thermal plasma with a range of temperatures up to \( \approx 0.9 \, \text{keV} \). We also showed that the X-ray hotspots are located \( \approx 1 \, \text{arcsec} \) farther away from the core than the radio hotspots. This is a second argument in support of our claim that X-ray and radio hotspots are due to different physical processes.

It is still not clear what is heating at least part of the X-ray-emitting gas to such high temperatures, particularly at the hotspots. We suggest two alternative scenarios. The first scenario is that the X-ray-emitting gas is the shocked interstellar medium, heated by the bow shock (advancing at a speed \( v_{\text{bs}} \)) to a temperature \( kT = (3/16) \, \mu_{\text{H}} v_{\text{bs}}^{2} \). In this case, the X-ray hotspots mark the position of the bow shock and the radio hotspots mark that of the reverse shock into the ejecta. To produce temperatures \( \approx 0.9 \, \text{keV} \) (as required by our fits with raymond-smith and most other thermal plasma models in xspec), the bow shock velocity (i.e. the expansion velocity along the major-axis) would have to be \( \approx 900 \, \text{km s}^{-1} \), almost four times higher than the expansion velocity measured by PSM10 from the width of the optical lines. However, their slit position was almost parallel to the minor-axis and did not include the hotspots; moreover, the viewing angle of the major-axis is still unknown. Thus, we still do not know at what speed the jet heads are advancing into the interstellar medium. Besides this, we noted in Section 4.1 that a sdedov model gives a good fit of the hotspot emission with thermal plasma temperatures as low as \( \approx 0.5 \, \text{keV} \), requiring a more plausible shock velocity \( \approx 300 \, \text{km s}^{-1} \). To sum up, we cannot yet rule out the
fast bow shock scenario for S26. An example of an X-ray-emitting bow shock located ahead of the radio-emitting lobes can be seen in the nearest radio galaxy Cen A (Kraft et al. 2007). An alternative scenario, considered more likely by PSM10, is that the bow shock is not advancing fast enough to produce the X-ray-emitting gas, and the shocked interstellar gas between the bow shock and the contact discontinuity has already cooled and collapsed to a thin, dense shell. In this case, the X-ray-emitting gas is located between the reverse shock and the swept-up outer shell and is heated by the shocked ejecta via thermal conduction. Most of the mass in the hot region must come from mass loading of denser interstellar clouds during the bubble expansion and from the evaporation of a part of the swept-up shell of interstellar medium, and its mixing with the lower density, hotter jet material.

The physical size of the X-ray hotspots is $\lesssim 20$ pc in radius and the projected size of the whole bubble is $\sim 300 \times 150$ pc. From the estimated emission measures (Tables 3–5), we infer a mass of X-ray-emitting gas approximately a few times $10^3 \, M_\odot$ in the hotspots (see also PSM10) and approximately a few times $1000 \, M_\odot$ in the cocoon (assuming a filling factor of $\sim 1$). These values are several orders of magnitude higher than the mass that could have been carried out by the BH jet and winds over the source lifetime. However, the mass of X-ray-emitting gas is an order of magnitude less than the total mass of the swept-up interstellar medium, that is, the swept-up shell is not significantly depleted by evaporation into the hot region, in agreement with the self-similar approximation of Weaver et al. (1977). From the estimated mass and fitted X-ray temperatures, we conclude that the X-ray-emitting gas contains a thermal energy $\sim 10^{51}$ erg (hotspots) and $\sim 10^{52}$ erg (whole cocoon) and we have showed earlier that the total thermal energy is $\sim 10^{53}$ erg and the energy carried by the synchrotron-emitting relativistic electrons is approximately a few times $10^{50}$ erg. The cooling time-scale of the X-ray-emitting gas in the cocoon is $\sim 10^7$ yr, 100 times longer than the age of the source. This is consistent with an emitted X-ray luminosity $\sim 10^{37}$ erg s$^{-1}$ even though power may have been transferred from the jet to the $\sim 0.3$–1 keV component of the gas at an average rate $\sim 10^{39}$ erg s$^{-1}$. By analogy with other shock-heated bubbles, we suggest that there may be even hotter but much less dense gas components, especially near the hotspots, whose hard X-ray emission would be too faint to be detected in the 50-ks Chandra observation.

6 CONCLUSIONS

We have carried out a multiband study of the shock-ionized bubble S26 in NGC 7793, which looks like a long-sought analogue of the Galactic jet source SS 433/W50, but on an even grander scale (projected size $\sim 300 \times 150$ pc). We showed that its structure is a scaled-down version of powerful FR II radio galaxies, with a core, radio lobes, X-ray hotspots and cocoon. It is the first time that all these elements have been found in a non-nuclear BH. We showed that the radio and X-ray hotspots are not spatially coincident: the X-ray hotspots are $\approx 20$ pc farther out than the peak of the radio intensity in the lobes. This suggests that X-ray and radio emission come from different populations of radiating particles. Based on our Chandra spectral analysis, we argued that the X-ray emission from the hotspots is most likely thermal. From the ATCA data, we showed that the radio emission from the lobes has a steep spectrum, consistent with optically-thin synchrotron emission. Over the rest of the cocoon, the radio spectrum is flatter, suggesting an additional contribution from free–free emission; this is consistent with what we would expect from the measured Hβ line emission. A point-like radio core is not detected, but the radio spectrum is flat or inverted in the proximity of the X-ray/optical core position; this may be interpreted as a more recent ejection. However, deeper ATCA observations are needed (and scheduled) to test this suggestion.

The total particle energy in the bubble is $\sim 10^{53}$ erg. Based on the measured radio flux and size of the bubble, and using standard equipartition relations for microquasar lobes, we estimated that the energy carried by the synchrotron-emitting relativistic electrons is a few 100 times less than the energy stored in protons, nuclei and non-relativistic electrons; non-relativistic particles provide most of the pressure to inflate the bubble. This system can give us important clues on how BHs at near-Eddington accretion rates transfer energy to the surrounding medium. The size and total energy content of the bubble are comparable to those found in some ULXs. However, here, the core appears to be currently X-ray faint (and was so also during the Einstein and ROSAT observations), while the jet is carrying a long-term average power $\sim 10^{40}$ erg s$^{-1}$ (PSM10). We do not have any information on the long-term-average X-ray luminosity of the core, so we cannot exclude that it is similar to the mechanical power. If the BH in S26 is of stellar origin, its super-Eddington jet power may force us to rethink the ‘canonical’ scheme of BH accretion states. In Galactic BH transients, a collimated jet is present at accretion rates less than or equal to a few per cent of the Eddington rate (low/hard state). At higher accretion rates ($\sim \text{0.05}–\text{0.5}$ Eddington), the accretion flow usually collapses to a geometrically-thin, radiatively-efficient thermal disc, and the jet is quenched. At even higher accretion rates (above Eddington), high X-ray luminosity and powerful mass-loaded outflows may coexist, but it is not known whether there can also be steady, collimated jets, and what their power is compared with the radiative power. S26 suggests that there can be collimated jets and they may even dominate over the radiative output. The same scenario has been suggested for some powerful FR II radio galaxies and quasars (Punsly 2007; Ito et al. 2008).

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\( \gamma \) is the total energy density including relativistic and non-relativistic particles (i.e. \( \epsilon_c \)). To express the relative contribution of nuclei and electrons.

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\( \epsilon_0 \) is the energy density in relativistic particles (electrons and protons), where \( k \) is a free parameter, \( \epsilon_0 \) is the energy density in the magnetic field; the high-energy cut-off. We introduce the following quantities:

APPENDIX A: SYNCHROTRON EMISSION IN THE MINIMUM-ENERGY CONDITION

To estimate the minimum energy associated with the synchrotron-emitting cocoon, we assume an energy range \( (\gamma_{\text{max}}, \gamma_{\text{min}}) \) for the relativistic electrons (Pohl 1993; Bicknell 2005), rather than a frequency range. Typical empirical values of \( \gamma_{\text{min}} \) are \( \sim 1-10 \) (Blundell & Rawlings 2000) and that of \( \gamma_{\text{max}} \) are \( \sim 10^4-10^5 \). For a steep spectrum, the minimum energy depends only very weakly on the high-energy cut-off. We introduce the following quantities: \( \epsilon_0 \) is the energy density in relativistic electrons, \( \epsilon_0 \equiv (1 + k \epsilon_c) \). We use the parameter \( \epsilon_0 \) that is that there is solid observational evidence (Willott et al. 1999; Leahy & Gizani 2001; Punsly 2007; Cavagnolo et al. 2010) that most of the energy in the lobes and cavities of radio galaxies is in low-energy electrons and other non-relativistic particles (i.e. \( \epsilon_0 \approx 1 \)) and that the energy density of the magnetic field may be \( \sim 10 \) times less than the total particle energy density, and within the relativistic energy density component, we use the parameter \( k \) to express the relative contribution of nuclei and electrons.

Applying the minimum-energy condition leads, after some algebra (Bicknell 2005), to the following expression for the...
minimum-energy magnetic field:

\[ B_{\text{min}}^2 = \left( \frac{m_e}{e} \right)^2 \frac{p + 1}{2} \left( 1 + k \right) C^{-1}(p) \frac{c}{m_e} \]

\[ \times \left[ h(p, \eta_{\text{min}} - \eta_{\text{max}}) L_v \frac{\nu^{(p-1)/2}}{2\epsilon_c} \right]^{4/(p+5)} \]

\[ \approx \left( \frac{m_e}{e} \right)^2 \frac{c}{m_e} \left[ \frac{3}{4\pi} \right]^{4/(p+5)} \]

\[ \times \left[ \frac{p + 1}{2} \left( 1 + k \right) C^{-1}(p) \right]^{4/(p+5)} \]

\[ \times \left[ \frac{1}{2} \left( 1 + k \right) C^{-1}(h) \right]^{4/(p+5)} \]

\[ \approx \frac{3}{4\pi} \frac{c}{m_e} \eta^{4/(p+5)} \nu^{2(p-1)/(p+5)} \]

\[ \times \mu_{\text{min}}^{2(p+5)/(p+1)} \lambda \]  

(A1)

where the energy spectrum of the electrons is \( N(E) = E^{-p} \). \( m_e \) and \( e \) are the electron mass and charge, respectively, \( c \) is the speed of light, \( I_0 \) is the specific surface brightness, \( S \) is the specific flux at the observer’s position, integrated over the whole cocoon, \( r_c \) is the cocoon radius, and \( D \) is the distance to the source. We have assumed a filling factor of 1, for simplicity. The functions

\[ h(p, \eta_{\text{min}} - \eta_{\text{max}}) = \frac{1}{p - 2} \left[ \gamma_{\text{min}}^{(2-p)} - \gamma_{\text{max}}^{(2-p)} \right] \]

(A2)

\[ C(p) = \frac{3^{p/2}}{2^{p+1/2} \pi^{(p+2)/2}} \]

\[ \times \Gamma \left( \frac{3}{2} + \frac{p}{2} \right) \left( \frac{p}{2} - \frac{1}{2} \right) \frac{1}{\Gamma \left( \frac{p}{2} + \frac{1}{2} \right)} \]

(A3)

and \( \Gamma(z) \) is the Gamma function. The corresponding total (minimum) energy density is

\[ \epsilon_{\text{tot,min}} = \left( 1 + k \right) \epsilon_c + \epsilon_{\text{min}} = \left( \frac{4}{p + 1} + 1 \right) \frac{B_{\text{min}}^2}{2\mu_0} \]

(A4)

We now need to relate the energy density, \( \epsilon_{\text{tot,min}} \), to the input jet power and size of the bubble. An approximate expression we could use is that the total energy (relativistic, non-relativistic and field) is simply \( \mathcal{P} t \). However, this is not entirely correct, because part of the injected energy is spent to inflate the bubble. From the self-similar solution of Weaver et al. (1977), we obtain a more accurate expression for the energy still available:

\[ \epsilon_{\text{tot}} = \frac{3}{4\pi} \frac{5}{11} \mathcal{P} r_c^{-3} \epsilon_c \]

(A5)

and according to our definition of \( \eta \),

\[ \epsilon_{\text{tot}} = \frac{3}{4\pi} \frac{5}{11} \eta \mathcal{P} r_c^{-3} \]

(A6)

In the minimum-energy approximation, from equation (A4)

\[ \left( \frac{B_{\text{min}}^2}{2\mu_0} \right) = \frac{3}{4\pi} \frac{5}{11} \eta \left( \frac{p + 1}{2} \right) \mathcal{P} r_c^{-3} \]

(A7)

and this value can now be substituted into equation (A1). Finally, the cocoon radius, \( r_c \), is obtained from the set of self-similar solutions of Weaver et al. (1977) (assuming a thin outer shell):

\[ r_c \approx \frac{125}{154\pi} \left( \frac{\mathcal{P}}{\rho_0} \right)^{1/5} \approx 0.76 \times \left( \frac{\mathcal{P}}{\rho_0} \right)^{1/5} \]

(A8)

and this expression is also substituted into equation (A1). (Note that here it is the total jet energy \( \mathcal{P} t \) that determines the size of the bubble.)

Rearranging equation (A1) with such substitutions, we obtain

\[ S_{\nu} \approx 1.84 \left( \frac{0.40 \eta}{\mathcal{P}} \right)^{1/(p+5)} \frac{\nu^{2(p-1)/5}}{\mu_0} \]

\[ \times \left[ \frac{1}{2} \left( 1 + k \right) C^{-1}(h) \right]^{-1} \]

\[ \times \frac{\nu^{4(p+1)/5}}{\rho_0} \]

(A9)

where the numerical values of \( h \) and \( C \) come from equations (A2) and (A3). For a spectral index \( \alpha \approx -0.5 \) and \( \gamma_{\text{min}} \lesssim 10 \) and \( \gamma_{\text{max}} \sim 10^5 \), we have, in physical units,

\[ S_{\nu} \approx 640 \left( 1 + k \right)^{-1/4} \nu^{7/4} \mathcal{P}_{\nu}^{1.3} \eta_1^{0.4} \nu_5^{0.5} d_2^{-2} \]

(A10)

where \( \mathcal{P}_{\nu} \) is the jet power in units of \( 10^{39} \) erg s\(^{-1}\), \( \nu_5 \) is the source age in units of \( 10^5 \), \( n_1 \) is the interstellar number density in cm\(^{-3}\), \( d \) is the source distance in Mpc, \( \nu_5 \) is the observed frequency in units of 5 GHz; the numerical coefficient is not very sensitive to the choice of \( \gamma_{\text{min}} \). We can obtain an analogous estimate for a spectral index \( \alpha \approx -0.7 \) (corresponding to \( p \approx 2.4 \)), which is more often the case in radio lobes. In that case,

\[ S_{\nu} \approx 82 \left( 1 + k \right)^{-1} \eta^{1.85} \mathcal{P}_{\nu}^{0.34} \eta_1^{0.32} n_1^{0.51} d_2^{-2} \nu_5^{-0.7} \]

(A11)

where we have fixed this time \( \gamma_{\text{min}} = 1 \).

We can now compare these specific fluxes with the observations: S26 has 5.5-GHz flux \( \approx 2 \) mJy and for a jet power approximately a few times \( 10^{39} \) erg s\(^{-1}\), at a distance of 3.9 Mpc. This tells us that \( (1 + k)^{-1} \times \eta^{1.85} \sim 10^{-3} \), that is, the energy stored in synchrotron-emitting relativistic electrons [a fraction \( \eta/(1 + k) \) of the total] is much less than the energy stored in relativistic protons and in non-relativistic particles. We cannot determine the individual values of \( \eta \) and \( k \), only the combination of those two quantities. If we use cosmic rays as an analogy (since they may be accelerated in jet and supernova shocks), we would expect \( k \sim 100 \). For plausible values of \( k \sim 10-100 \), \( \eta/(1 + k) \sim \) a few times \( 10^{-3} \).

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