A dark jet dominates the power output of the stellar black hole Cygnus X-1

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Accreting black holes are thought to emit the bulk of their power in the X-ray band by releasing the gravitational potential energy of the infalling matter\textsuperscript{1}. At the same time, they are capable of producing highly collimated jets of energy and particles flowing out of the system with relativistic velocities\textsuperscript{2}. Here we show that the 10 solar mass black hole in the X-ray binary Cygnus X-1\textsuperscript{3,4,5} is surrounded by a large-scale (about 5 pc in diameter) ring-like structure that appears to be inflated by the inner radio jet\textsuperscript{6}. We estimate that in order to sustain the observed emission of the ring, the jet of Cygnus X-1 has to carry a kinetic power that can be as high as the bolometric X-ray luminosity of the binary system. This result may imply that low-luminosity stellar mass black holes as a whole dissipate the bulk of the liberated accretion power in the form of ‘dark’, radiatively inefficient relativistic outflows, rather than locally in the X-ray emitting inflow.
Relativistic jets are a common feature of accreting black holes on all mass scales, from super-massive black holes at the centres of active galactic nuclei\textsuperscript{7,8} to stellar mass black holes in X-ray binary systems within our own Galaxy\textsuperscript{9,10,11}. While the inflow of hot gas can be very efficient in producing light (up to $\sim 40$ per cent of the accreted material may be transformed into energy and radiated away in the form of optical/UV/X-ray photons) the same is not true for the synchrotron-emitting outflow, whose efficiency might be lower than a few per cent. Estimating the total – radiated plus kinetic – power content of the jets, and hence their importance with respect to the accretion process in terms of energetics, is a primary aim of high energy astrophysics.

We observed the field of the 10 solar mass black hole and Galactic jet source Cygnus X-1 at 1.4 GHz for 60 hours with the Westerbork Synthesis Radio Telescope (WSRT), yielding the deepest low frequency radio observation of that region to date\textsuperscript{12}. A ring of radio emission – with a diameter of $\sim 1$ million AU – appears northeast of Cygnus X-1 (Figure 1), and seems to draw an edge between the tail of the nearby HII nebula Sh2-101\textsuperscript{13} (whose distance is consistent with that to Cygnus X-1\textsuperscript{14}) and the direction of the radio jet powered by Cygnus X-1\textsuperscript{6}. Since Cygnus X-1 moves in the sky along a trajectory which is roughly perpendicular to the jet\textsuperscript{15,6,16}, and thus can not possibly be traced back to the ring centre, this rules out that the ring might be the low-luminosity remnant of the natal supernova of the black hole. In analogy with extragalactic jet sources, the ring of Cygnus X-1 could be the result of a strong shock that develops at the location where the collimated jet impacts on the ambient interstellar medium (Figure 2). The jet particles inflate a radio lobe which is over-pressured with respect to the surroundings, thus the lobe expands sideways forming a spherical bubble of shock-compressed ISM, which we observe as a ring because of
limb brightening effects. The collisionally ionized gas behind the bow shock would produce the observed bremsstrahlung radiation; in addition, if the shock is radiative, significant line emission is expected from hotter gas at the bow shock front. Structures similar to the ring of Cygnus X-1 have been found at the edges of radio lobes inflated by the jets of super-massive black holes at the centre of powerful radio galaxies\textsuperscript{17}, where the much higher temperatures of the intra-cluster medium compared to the ISM shift the bremsstrahlung emission to X-ray frequencies. Striking confirmation of this interpretation comes from follow-up optical observations of the field of Cygnus X-1 with the Isaac Newton Telescope Wide Field Camera: the ring is clearly detected using a H\textalpha filter in an exposure of only 1200 sec (Figure 3). The estimated flux of the ring at H\textalpha frequencies exceeds the measured radio flux by a factor $\gtrsim 20$, indicating that the collisionally ionized gas in the ring is indeed emitting bremsstrahlung radiation and also that a significant amount of the measured H\textalpha flux is due to line emission, as expected in the case of radiative shock.

Acting as an effective jet calorimeter, the ISM allows an estimate of the jet’s $power \times lifetime$ product\textsuperscript{18} that is, in principle, independent of the uncertainties associated with the jet spectrum and radiative efficiency. Following a self-similar fluid model developed for extragalactic jet sources\textsuperscript{19,20,21}, we assume that the jet of Cygnus X-1 is supplying energy at a constant rate $P_{\text{jet}}$, and is expanding in a medium of constant density. We set the minimum temperature of the thermal gas to $T_{\text{shock}} \approx 10^4 \text{K}$, a typical temperature above which the cooling time becomes critically short, and below which the ionization fraction becomes too low for the ring to emit observable bremsstrahlung radiation. Given the average ring monochromatic luminosity, we are able to estimate a density of about $1300 \text{ cm}^{-3}$ for the shock-compressed particles in the ring from the expression for the bremsstrahlung
emissivity\textsuperscript{22,23}. By balancing the interior pressure exerted by the lobe and the ram pressure of the shocked ISM, it can be shown\textsuperscript{20} that the jet length within the lobe grows with the time $t$ in such a way that: $t \simeq (L/2)^{(5/3)} \times (\rho_0/P_{\text{jet}})^{(1/3)}$, being $L$ the separation between Cygnus X-1 and the ring’s outermost point, and $\rho_0$ the mass density of the un-shocked gas. By writing the time derivative of this equation, there follows a simple relation between the jet lifetime, its length within the lobe, and the ring velocity: $t = \frac{3}{5} (L/v_{\text{ring}})$. For a strong shock in a mono-atomic gas, the expansion velocity is set by the temperature of the shocked gas. If the shock is radiative, then the initial post-shock temperature can be higher than that of the thermalized, bremsstrahlung-emitting gas. A stringent constraint comes from X-ray observations: from the non-detection of soft X-ray emission in a 12 ksec observation of Cygnus X-1 taken with the Chandra X-ray Observatory, we can place an upper limit of $T_{\text{shock}} \lesssim 3 \times 10^6$ K by modelling the emission as a radiative shock. This, combined with the lower limit of $10^4$ K, gives a ring velocity $v_{\text{ring}} \simeq 20 - 360$ km sec$^{-1}$. The resulting jet lifetime is $t \simeq 0.02 - 0.32$ Myr, to be compared with the estimated age of the progenitor of the black hole in Cygnus X-1, of a few Myr\textsuperscript{16}.

Adopting a mass density of the un-shocked gas that is 4 times lower than the initial post-shock density, we infer a time-averaged energy emission rate from the jet between $8 \times 10^{35}$ and $10^{37}$ erg sec$^{-1}$. Based upon daily X-ray and radio monitoring of Cygnus X-1 over the last 10 years, we know that Cygnus X-1 is in a hard X-ray state\textsuperscript{24} – and hence powers a collimated jet\textsuperscript{11} – for about 90 per cent of its lifetime. Taking this duty cycle into account, the total power carried by the jet of Cygnus X-1 is: $9 \times 10^{35} \lesssim P_{\text{jet}} \lesssim 10^{37}$ erg sec$^{-1}$, up to two orders of magnitude higher than the existing estimate based on the flat radio spectrum\textsuperscript{25}. The fact that the jet of Cygnus X-1
switches off for short periods of times (typically for a few months over timescales of years) does not violate the model assumptions: the condition of constant power supply is met as long as the jet is intermittent over timescales that are short compared to its lifetime. The total power carried by the jet is a significant fraction \( f \simeq 0.03 - 0.5 \) of the bolometric (0.1-200 keV) X-ray luminosity of Cygnus X-1 while in the hard state\textsuperscript{26}; the total energy deposited by the jet into the surrounding ISM over its lifetime is \( \simeq 7 \times 10^{48} \text{ erg} \).

The particle density of the ISM through which the ring is expanding is constrained between \( \sim 1 \) and about 300 cm\(^{-3}\), at most three orders of magnitude higher than the average ISM density in the Galaxy. The lack of a ‘counter-ring’ can be explain in terms of a much lower particle density in the opposite direction to Cygnus X-1. Such large density inhomogeneities are not unusual for dense star forming regions, such as the Cygnus association, and would support the hypothesis that the ring is the result of the interaction between the radio lobe and the tail of the HII nebula. If so, the counter-jet of Cygnus X-1 is travelling undisturbed to much larger distances, gradually expanding and releasing its enormous kinetic energy. This could mean that the ring of Cygnus X-1 is a rather exceptional detection for this class of objects, made possible by its proximity to the HII nebula. Taking into account the contribution of the counter-jet as well, the total power dissipated by the jets of Cygnus X-1 in the form of kinetic energy can be as high as the bolometric X-ray luminosity of the system \( (f = 0.06 - 1) \).

The results presented here have important consequences for low-luminosity stellar mass black holes \textit{as a whole}: several works\textsuperscript{27,28,29} have suggested that hard state stellar black holes
below a critical X-ray luminosity dissipate most of the liberated gravitational power in the form of radiatively inefficient outflows, rather than locally in the accretion flow. This is because in hard state black hole binaries the total jet power and the observed X-ray luminosity follow a non-linear relation of the form $P_{\text{jet}} \propto L_{X}^{0.5}$ (both expressed in Eddington units). Using the ring of Cygnus X-1 as an effective calorimeter for the jet power, we have constrained the normalization factor of the above equation, showing that $P_{\text{jet}} = fL_{X}$, with $f \simeq 0.06 - 1$, when $L_{X} \simeq 0.02$. Thus the critical X-ray luminosity below which $P_{\text{jet}} > L_{X}$ is no lower than a few $10^{-5}$ Eddington, and could even be as high as the peak luminosity of the hard X-ray state. This radically alters our concepts of the accretion process and of the feedback of accretion power into the surroundings. Via the new observations presented here we have strong evidence that the power output of low-luminosity – i.e. the overwhelming majority of – stellar black holes is dominated by the kinetic energy of ‘dark’ outflows, whose key signature is the eventual energisation of the ambient medium.

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1 arcmin (2 light years)
Figure 1: The interstellar gas around a Galactic stellar black hole is stirred by the pressure of a highly collimated relativistic jet of energy and particles, resulting in a 15 light-years wide ring of radio emission. The field of view of the 10 solar mass black hole in Cygnus X-1 (marked by a cross) was observed by the Westerbork Synthesis Radio Telescope for 60 hours at 1.4 GHz: the ring appears to draw an edge between the tail of Sh2-101, the nearby HII nebula on the left hand side, and the direction of the inner radio jet of Cygnus X-1 (shown in the inset of Figure 2). The spatial resolution in this map \((25 \times 14 \text{ arcsec}^2)\) is illustrated by the green open ellipse on the top right corner. The wedge shows the (logarithmic) flux scale, between 0–0.01 Jy; the average ring monochromatic flux is 0.2 mJy beam\(^{-1}\). At a distance of 2.1 kpc, the separation \(L\) between Cygnus X-1 (coincident with the jet base) and the ring’s outermost point is \(1.9 \times 10^{19} \times \sin(\theta)^{-1} \text{ cm}\), where \(\theta\) is the jet inclination to the line of sight \((\theta \simeq 35^\circ[5])\). Because of limb-brightening, we observe a ring whose thickness \(\Delta R\) in the plane of the sky equals the effective length we are looking through into the bubble. At 2.1 kpc, \(\Delta R \simeq 1.6 \times 10^{18} \text{ cm}\).
Figure 2: The ring of Cygnus X-1 is the result of a strong shock that develops at the location where the pressure exerted by the collimated milliarcsec-scale jet, shown in the inset, is balanced by the interstellar medium. The jet particles start to inflate a synchrotron-emitting lobe which is over-pressured with respect to the surrounding gas, thus the lobe expands sideways forming a spherical bubble of shock-compressed bremsstrahlung-emitting gas. The monochromatic luminosity of the ring, \( L_{1.4 \text{ GHz}} \approx 10^{18} \text{ erg sec}^{-1} \text{ Hz}^{-1} \), equals the product \((\epsilon_{\nu} \times V)\), where the source unit volume \(V\) is given by the beam area times the measured ring thickness: \( V \approx 4 \times 10^{53} \text{ cm}^3 \), and \( \epsilon_{\nu} \) is the expression of the bremsstrahlung emissivity for a pure hydrogen gas emitting at a temperature \( T \): 

\[
\epsilon_{\nu} = 6.8 \times 10^{-38} g(\nu, T) T^{-1/2} n_e^2 \exp(h\nu/k_B T) \text{ erg cm}^{-3} \text{ sec}^{-1} \text{ Hz}^{-1}
\]

(being \( h \) and \( k_B \) the Plank and Boltzmann’s constant, respectively). For \( T \approx 10^4 \text{ K} \) and a Gaunt factor \( g \approx 6 \), the density \( n_e \) of the ionized particles in the ring is \( n_e \approx 25 \text{ cm}^{-3} \). The ionization fraction at \( 10^4 \text{ K} \) is \( x \approx 0.02^{[23]} \), resulting in a total particle density \( n_t \approx 1300 \text{ cm}^{-3} \). The minimum pressure inside the lobe predicted by the model is \( \approx 5 \times 10^{-11} \text{ erg cm}^{-3} \). If this pressure is solely due to a magnetized relativistic pair plasma in equipartition, then the strength of the magnetic field is about 40 \( \mu \text{G} \). Assuming minimum energy conditions\(^{22}\), this yields an expected lobe synchrotron surface brightness of \( \approx 35 \text{ mJy beam}^{-1} \) at 1.4 GHz, more than 150 times brighter than the observed ring. The much lower upper limit for the lobe surface brightness means that either the system is far from equipartition, or the most of the energy is stored in non-radiating particles, presumably baryons.
Figure 3: Optical counter-part of the radio ring of Cygnus X-1. The optical image, taken with the Isaac Newton Telescope Wide Field Camera using an Hα filter, is shown with the 3σ radio contours over-plotted in white. As no calibration was taken during the observation, an absolute flux scale can not be set; however, given that the ring is clearly detected in a 1200 sec exposure, and taking into account the atmospheric and sky conditions during the observation, this translates into a minimum unabsorbed Hα flux of 0.02 mJy arcsec$^{-2}$. The corresponding radio-optical spectral index $a$ (defined such that $F_\nu \propto \nu^a$) is greater than 0.2. This implies an emission mechanism with flat spectrum, such as bremsstrahlung, plus excess flux possibly due to line emission, as expected in the case of radiative shock. For comparison, if the ring emitted optically thin synchrotron radiation with a spectral index $a = -0.7$, the expected flux at Hα frequencies would be $1.2 \times 10^{-7}$ mJy arcsec$^{-2}$, by no means detectable by the INT WFC in 1200 sec.