Very-high-energy particle acceleration powered by the jets of the microquasar SS 433

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SS 433 is a binary system containing a supergiant star that is overflowing its Roche lobe with matter accreting onto a compact object (either a black hole or neutron star)3. Two jets of ionized matter with a bulk velocity of approximately 0.26c (where c is the speed of light in vacuum) extend from the binary, perpendicular to the line of sight, and terminate inside W50, a supernova remnant that is being distorted by the jets1–4. SS 433 differs from other microquasars (small-scale versions of quasars that are present within our own Galaxy) in that the accretion is believed to be super-Eddington9–11, and the luminosity of the system is about 1040 ergs per second2,9,12,13. The lobes of W50 in which the jets terminate, about 40 parsecs from the central source, are expected to accelerate charged particles, and indeed radio and X-ray emission consistent with electron synchrotron emission in a magnetic field have been observed14–16. At higher energies (greater than 100 gigaelectronvolts), the particle fluxes of γ-rays from X-ray hotspots around SS 433 have been reported as flux upper limits17–20. In this energy regime, it has been unclear whether the emission is dominated by electrons that are interacting with photons from the cosmic microwave background through inverse-Compton scattering or by protons that are interacting with the ambient gas. Here we report teraelectronvolt γ-ray observations of the SS 433/W50 system that spatially resolve the lobes. The teraelectronvolt emission is localized to structures in the lobes, far from the centre of the system where the jets are formed. We have measured photon energies of at least 25 teraelectronvolts, and these are certainly not Doppler-boosted, because of the viewing geometry. We conclude that the emission—from radio to teraelectronvolt energies—is consistent with a single population of electrons with energies extending to at least hundreds of teraelectronvolts in a magnetic field of about 16 microgauss.

In the SS 433/W50 complex, several regions located west of the central binary (w1 and w2) and east (e1, e2, e3) are observed to emit hard X-rays5. Previous searches for very-high-energy (VHE) γ-ray emission from the hotspots between roughly 100 GeV and 10 TeV have produced null results17–20, though an excess observed at about 800 MeV may be associated with SS 433 and W501. The High Altitude Water Cherenkov (HAWC) observatory, Mexico, is a wide-field-of-view VHE γ-ray observatory surveying the Northern Hemisphere above 1 TeV, and is optimized for photon detection above 10 TeV22. SS 433 transits 15° from the zenith of the HAWC detector each day, and has been observed with >90% uptime since the start of detector operations in 2015. In 1,017 days of measurements with HAWC, an excess of γ-rays with a post-trials significance of 5.4σ has been observed in a joint fit of the eastern and western interaction regions of the jets of SS 433. The emission is plotted in galactic coordinates in Fig. 1, which includes an overlay of the X-ray observations of the jets and the central binary. The γ-ray emission is spatially coincident with the X-ray hotspots w1 and e1; no significant emission is observed at the location of the central binary where the jets are produced. Spatial and spectral fits to SS 433 are performed in a semicircular region of interest (ROI) designed to mask out diffuse emission from...
the Galactic plane. The ROI also removes significant spatially extended emission from the nearby γ-ray source MGRO J1908+06. The spatial distribution and spectrum of γ-rays from MGRO J1908+06 are fitted using an electron diffusion model23, and point-like sources centred on e1 and w1 are fitted on top of this extended emission. As a systematic check, the regions are also fitted using X-ray spatial templates and extended Gaussian functions. Neither improves the statistical significance of the fits. Upper limits on the angular size of the emission regions are 0.25° for the east hotspot and 0.35° for the west hotspot at 90% confidence. Given the distance to the source of 5.5 kpc, this corresponds to a physical size of 24 pc and 34 pc, respectively. The constraint is tighter on the eastern hotspot owing to its higher statistical significance.

The VHE γ-ray flux is consistent with a hard $E^{-2}$ spectrum, though current data from HAWC are not of sufficient significance to constrain the spectral index. Therefore, we report the flux of both hotspots at 20 TeV, at which systematic uncertainties due to the choice of spectral model are minimized and the sensitivity of HAWC is maximized. At e1, the flux is $2.4^{+0.8}_{-0.5} \times 10^{-16}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$, and at w1 the flux is $2.1^{+0.6}_{-0.5} \times 10^{-16}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$. HAWC detects γ-rays from the interaction regions up to at least 25 TeV. The energies of these γ-rays are a factor of three to ten higher than previous measurements from microquasars24,25. Since most γ-ray telescopes are optimized for measurements below 10 TeV, this may explain why these photons were not observed in previous observational campaigns.

Figure 1: VHE γ-ray image of the SS 433/W50 region in Galactic coordinates. The colour scale indicates the statistical significance of the excess counts above the background of nearly isotropic cosmic rays before accounting for statistical trials. The figure shows the γ-ray excess measured after the fitting and subtraction of γ-rays from the spatially extended source MGRO J1908+06. The jet termination regions e1, e2, e3, w1 and w2 observed in the X-ray data are indicated, as well as the location of the central binary. The solid contours show the X-ray emission observed from this system.

HAWC observations of the e1 and w1 regions can be tested. The first is that protons are primarily responsible for the observed γ-rays. Protons must have an energy of at least 250 TeV to produce 25-TeV γ-rays through hadronic collisions with ambient gas. Proton–proton collisions yield neutral pions ($\pi^0$) that decay to VHE γ-rays, and charged pions ($\pi^\pm$) that decay to the secondary electrons and positrons responsible for radio to X-ray emission via synchrotron radiation. This scenario is of particular interest because there is spectroscopic evidence for ionized nuclei in the inner jets of SS 4338,26. The alternative scenario requires electrons of at least 130 TeV to up-scatter the low-energy photons from the cosmic microwave background (CMB) to 25-TeV γ-rays. In this case, the radio to X-ray emission is dominated by synchrotron radiation from the same population of electrons in the magnetized plasma of the jets and lobes.

The fact that the VHE emission is detected along a line of sight nearly orthogonal to the jet axis means that charged particle trajectories become isotropic before they interact to produce the γ-rays. The embedded magnetic fields in the VHE regions can easily deflect the accelerated particles because their typical gyroradii are much smaller than the size of the emission regions, approximately 30 pc. The jets are only mildly relativistic, so the emission from the interaction regions will have a negligible Doppler beaming effect and remain nearly isotropic.

The flux of VHE γ-rays observed by HAWC makes the proton scenario for SS 433 unlikely, because the total energy required to produce the highly relativistic protons is too high. The jets of SS 433 are known to be radiatively inefficient, with most of the jet energy transformed into the thermal energy of W5028,29 rather than into particle acceleration. We model the primary proton spectrum as a power law with an exponential cutoff, $dN/dE_p \propto E_p^{-\alpha} \exp(-E_p/1 \text{ PeV})$. If we assume that 10% of the jet kinetic energy converts into accelerated protons, and that the ambient gas density is $0.05 \text{ cm}^{-3}$, then the resulting flux of γ-rays from proton–proton collisions is much less than the observed γ-ray flux, as shown in the dash-dotted line of Fig. 2. In fact, for a target proton density as large as $0.1 \text{ cm}^{-3}$ in the e1 region28,29, the total energy of the proton population needs to be around $3 \times 10^{40}$ erg to explain the observed γ-rays, assuming an $E_{\gamma}^{-2}$ spectrum. This is comparable to the total jet energy available during the presumed 30,000-year lifetime2 of SS 433. Furthermore, because the synchrotron emission from secondary electrons from charged pion decay is always lower than the γ-ray flux from $\pi^0$ decay, and the observed X-ray flux is higher than the γ-ray flux, the X-rays cannot originate solely from secondary electrons.

Finally, the proton scenario requires that the protons remain trapped in the region observed by HAWC for the lifetime2 of SS 433. This means the protons must diffuse very slowly, with a diffusion coefficient of about $1/1,000$ of the typical value28 of the interstellar medium (ISM), $D_{\text{ISM}} \approx 3 \times 10^{28} (E/3 \text{ GeV})^{1/2} \text{ cm}^2 \text{ s}^{-1}$. This value, comparable to the theoretical Bohm limit, is very small but not impossible. Given the uncertainties in the historical jet flux, the ambient particle density and the radiative efficiency, we cannot exclude the possibility that some fraction of the γ-ray flux is produced by protons. However, we do rule out the possibility that the VHE γ-rays are entirely produced by protons.

Highly relativistic electrons, on the other hand, can produce γ-rays much more efficiently, primarily via inverse Compton scattering of CMB photons to γ-rays. The inverse Compton losses due to up-scattering of infrared and optical photons are suppressed owing to the Klein–Nishina effect and are thus dominated by scattering of CMB photons29. In this scenario, the ratio of the VHE γ-ray to X-ray fluxes constrains the energy density in the magnetic field compared to the energy density in CMB photons. We have modelled the broadband spectral energy distribution of the eastern emission region 15' to 33' from the centre of SS 433. The solid and dashed lines in Fig. 2 show the spectral energy distribution of a leptonic model for e1 produced by an injected flux of relativistic electrons with an energy spectrum $dN/dE \propto E^{-\alpha} \exp(-E/E_{\text{max}})$ in a magnetic field of strength $B$. We use the parameters $\alpha = 1.9$, $E_{\text{max}} = 3.5 \text{ PeV}$, and $B = 16 \mu \text{G}$ (see Methods).

The estimate of the magnetic field strength is consistent with the
The maximum electron energy of about 1 PeV has important implications for electron acceleration sites and acceleration mechanisms in SS 433. SS 433 is distinguished from other binary systems with relativistic objects because it achieves a supercritical accretion of gas onto the central engine (the compact object)\(^2\). Powerful accretion flows and the inner jets near the compact object have therefore been proposed as possible acceleration sites of relativistic particles\(^{26}\). However, the observation from HAWC suggests that ultrarelativistic electrons are not accelerated near the centre of the binary. If the electrons were accelerated in the central region, they would have cooled by the time they reached the sites of observed VHE emission. Owing to their small gyroradii, high-energy electrons may transport energy in a magnetized medium via diffusion or advection. The distance travelled via diffusion within the cooling time \(t_{\text{cool}}\) of an electron of energy \(E\) moving in a magnetic field of strength \(B\) is \(r_d = 2\sqrt{D t_{\text{cool}}} \approx 36 \text{ pc} (E/\text{1 PeV})^{-1/3} (B/16 \mu\text{G})^{-2}\), using the diffusion coefficient \(D\) typical of the ISM\(^{28}\). This distance would be even smaller for diffusion coefficients lower than the ISM value. Similarly, the distance travelled by electrons being advected with the jet flow is \(r_{\text{adj}} = 0.26c \times t_{\text{cool}} \approx 4 \text{ pc} (E/\text{1 PeV})^{-1} (B/16 \mu\text{G})^{-2}\) for a jet velocity of 0.26c. Both distance scales are smaller than the 40 pc distance between the binary and e1, indicating that the electrons are not accelerated near the centre of the system.

Instead, the highly energetic electrons in SS 433 are probably accelerated in the jets and near the VHE \(\gamma\)-ray emission regions. This presents a challenge to current acceleration models. For example, particle acceleration may be driven by the dissipation of the magnetic fields in the jets, but above several hundred teraelectronvolts the electron acceleration time exceeds the electron cooling time, assuming a 16-\(\mu\)G magnetic field. Thus, the system does not appear to have sufficient acceleration power, unless there are very concentrated magnetic fields along the jets. If instead particle acceleration is driven by standing shocks produced by the bulk flow of the jets, it is possible to reach petaelectronvolt energies if the size of the acceleration region is larger than the gyroradii of the electrons. However, shocks in the interaction regions are not currently resolved by X-ray or \(\gamma\)-ray measurements.

Studies of microquasars such as SS 433 provide valuable probes of the particle acceleration mechanisms in jets, since these objects are believed to be scale models of the much larger and more powerful jets in active galactic nuclei\(^{30}\). Active galactic nuclei are the most prevalent VHE extragalactic sources and are believed to be the sources of the highest-energy cosmic rays. Although active galactic nuclei are not spatially resolved at VHE energies, with this observation we have identified a VHE source in which we can image the particle acceleration powered by jets. Future high-resolution observations of SS 433 are possible using atmospheric Cherenkov telescopes pointed to localize the emission sites better, and further high-energy measurements with HAWC will record the spectrum at high energies and better constrain the maximum energy of accelerated particles.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41586-018-0565-5.

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Methods

Data reduction and maximum likelihood analysis. This analysis uses 1,017 days of data from the High Altitude Water Cherenkov (HAWC) Observatory collected between 26 November 2014 and 20 December 2017. The HAWC Observatory is an array of 300 tightly packed identical water Cherenkov detectors deployed 4,100 m above sea level on the slope of the volcano Sierra Negra, Mexico1. Each detector is a cylindrical water tank standing 5 m tall and 7.3 m in diameter, filled with 180,000 liters of purified water. At the bottom of each tank are four photomultipliers (PMTs) facing upward. The PMTs record the Cherenkov photons created by the relativistic secondary particles produced when primary cosmic rays and γ-rays interact at the top of the atmosphere. The HAWC array covers 22,000 m². Its construction ended in December 2014, and the full array was commissioned in March 2015.

Using the relative arrival time of photoelectrons (hits) detected by the PMTs, the arrival direction of primary γ-rays can be reconstructed with an accuracy15 of around 1° below 1 TeV to 0.2° above 10 TeV. The accuracy of the reconstruction determines the point spread function of the detector, and is a function of the energy, zenith angle and composition of the primary particle. Air showers from γ-rays are discriminated from the nearly isotropic background of hadronic cosmic rays by filtering out ‘clumpy’ patterns of hits, which are characteristic of the energy deposited in hadronic air showers. The cosmic-ray background rejection efficiency improves rapidly as a function of energy12, increasing from 90% at 1 TeV to 99.9% at 10 TeV.

To compute the statistical significance of γ-ray emission observed with HAWC, a maximum likelihood fit using parametric spatial and spectral models is applied to the data13. The models are forward-folded through the detector response to produce expected counts of γ-ray signal events and cosmic-ray background events. The expectation is then compared to the observed counts N_{obs}. To calculate the expected counts as a function of position on the sky, the events are binned in a fine mesh using the HEALPix pixelization of the unit sphere35. The pixelization is chosen to be 0.1°, roughly two to five times smaller than the radius of the instrument point spread function. To apply models of the energy spectrum of a source, the data are binned according to the fraction of PMTs in the detector triggered by an air shower35. This measure of shower ‘size’ is used as a coarse proxy for the energy of the primary particle; a total of nine size bins labelled B = 1–9 is used. Given a model θ with spatial and spectral parameters, we maximize the likelihood of the model having produced the data as follows:

\[ \ln C(N_{\text{obs}} | \theta) = \sum_{j=1}^{9} \sum_{B} \ln(N_{\text{obs}}(\theta,B) - \ln(N_{\text{obs}}(\theta,j))) \]

where the sum runs over the size bins B and the HEALPix pixels j in the region of interest (ROI) of the fit. P is the Poisson probability of detecting N_{obs} events in pixel j and size bin B given the model parameters θ.

Within the ROI around SS 433 defined in Extended Data Fig. 1, two fits are performed to maximize the likelihood: a fit which accounts only for the emission from MGRO J1908+06 (null hypothesis), and a fit that accounts for the combined emission from MGRO J1908+06 and the SS 433 region (alternative hypothesis). The ratio of the maximum likelihood defines a test statistic (TS):

\[ \text{TS} = 2(\ln C(N_{\text{obs}} | \theta_{\text{null}}) - \ln C(N_{\text{obs}} | \theta_{\text{alt}})) \]

where θ_{null} and θ_{alt} represent the spatial and spectral parameters of the null and alternative hypotheses, respectively. TS is then converted to a P value to estimate the statistical significance of emission from SS 433. As discussed in the main text, the alternative hypothesis assumes two point sources with power-law spectra dN/dE = f_0(E/E_0)^{-\gamma} TeV^{-1}, where the flux normalization f_0 is the free parameter of the spectral model.

Wilks’ Theorem is used to convert TS to a P value36. In the joint likelihood maximization, there are two degrees of freedom (d.o.f.) for the two separately fitted flux normalizations of the hotspots at w1 and e1. Therefore, we calculate the one-tailed P value for (TS > x^2 = 41.2[d.o.f. = 2]) = 1.13 × 10^{-7}. This is the tail probability of TS > 41.2 assuming that, under the null hypothesis of no excess γ rays, TS follows a χ^2 distribution with 2 degrees of freedom. Since the positions of the point source fits at w1 and e1 were chosen after looking into the data, and because we are searching for other microquasars in the field of view of HAWC, we must apply a posteriori corrections to the P value to account for multiple-comparison effects.

The X-ray interaction regions w1, w2, e1, e2 and e3 are a priori candidates for the locations of the maxima, as is the centre of the binary system, for a total of six potential hotspots. Given the angular resolution of HAWC, it would not be possible to spatially resolve all six hotspots; at best three regions (east, west and centre) can be separately fitted with confidence. There are 23 possible combinations of the six a priori locations that can be used to fit one, two or three hotspots in the eastern, central and western regions of the source. We add an additional 12 trials to account for the known microquasars in the field of view of HAWC14,15. This trial factor is conservative given that several Galactic microquasars are already known teraelectronvolt sources16,17. Given 35 total trials, the corrected P value is 3.96 × 10^{-8}, which corresponds to a statistical significance of 5.4σ.

Modelling of the nearby extended source MGRO J1908+06. A bright extended source, MGRO J1908+06, is detected with more than 30σ in this dataset and is located less than 2° from the γ-ray hotspots of SS 433 (Extended Data Fig. 1). The region of MGRO J1908+06 contains a pulsar and a supernova remnant, but it is not clear whether the observed teraelectronvolt γ-ray emission is from either or both of them. A detailed discussion of MGRO J1908+06 is beyond the scope of this paper. However, the morphology of MGRO J1908+06 must be carefully studied to minimize the contamination of the emission due to MGRO J1908+06 on the fluxes of the lobes.

A maximum likelihood analysis is performed that simultaneously fits the emission from MGRO J1908+06 and the hotspots at w1 and e1. An electron diffusion model appropriate for older pulsar wind nebulae38,39 is used to describe the spatial morphology of MGRO J1908+06. Given the uncertainty of the nature of MGRO J1908+06, two other spatial models with Gaussian and power law radial profiles are also tested in the simultaneous fit. The choice of spatial model affects the best-fit fluxes from w1 and e1 at the level of ±20%. We adopt this value as a systematic uncertainty on the flux from w1 and e1 due to VHE emission from the nearby extended source.

Contamination from galactic diffuse emission. The e1 and w1 regions are located roughly 2° from the Galactic plane, so the contamination from the Galactic diffuse emission (GDE) is negligible. However, MGRO J1908+06 has a Galactic latitude of about 1°. Since the three spatial models used to fit MGRO J1908+06 are radially symmetric, the presence of GDE has the potential to produce an overestimate in the flux from MGRO J1908+06, which could result in an underestimate in the flux measured from w1 and e1. To minimize the effect of the GDE on the fit, the ROI is defined to be a semicircular region centred on the position of MGRO J1908+06 (Extended Data Fig. 1). The ROI is designed to reduce the effect of GDE by excluding the half of the source closest to the Galactic plane.

To estimate the systematic uncertainties associated with the choice of ROI and possible contamination from GDE, a second maximum likelihood fit is performed using a full-disk ROI that includes GDE, emission from MGRO J1908+06, and w1 and e1. The spatial distribution of the GDE is modelled with a Gaussian profile of three different widths of 0.5°, 1° and 2° in Galactic latitude, and is treated as constant in Galactic longitude over the width of the ROI. Comparing the results to the fit with a semicircular ROI indicates that contamination from GDE is less than 10% for e1 and less than 20% for w1.

Fit results. The fit results are reported in Extended Data Table 1. Fitting the emission from w1 and e1 simultaneously, we calculate TS = 41.2, which corresponds to a 5.4σ observation (P = 3.96 × 10^{-8}) after accounting for a posteriori statistical trial factor. To check the consistency of the fit, we redefined the alternative model to include MGRO J1908+06 and only e1 or w1; the significance of the VHE excess from these locations is below 5σ in the fits, but the estimated fluxes are consistent with the simultaneous fit. An additional check is made on the effect of fixing versus floating the best-fit positions of the emission from the east and west hotspots. In the original alternative hypothesis, the point sources are centred on e1 and w1. Here, the positions of the point sources are made additional free parameters in the point source fit. We find that allowing the positions of the teraelectronvolt hotspots to vary does not affect the flux estimates, which are consistent with the fixed-position fits. Moreover, the best-fit positions of the east and west teraelectronvolt emission regions are consistent with e1 and w1 within statistical uncertainties.

The choice of spectral model also affects the estimated γ-ray flux at 20 TeV. Extended Data Table 2 shows the dependence of the best-fit VHE flux from e1 and w1 on the assumed spectral models, including statistical uncertainties on the flux normalization at 20 TeV. Two spectral models were tested: a simple power law dN/dE ∝ E^\gamma, and a power law with an exponential cutoff dN/dE ∝ E^\gamma exp(-E/E_c). The choice of spectral model can alter the flux normalization by almost a factor of two compared to the default E^-2 model.

Summary of systematic uncertainties. The systematic uncertainties in the estimated fluxes from the teraelectronvolt hotspots of SS 433 include the following contributions: detector systematic effects, modelling ambiguities in MGRO J1908+06, and contamination from Galactic diffuse emission. The systematic uncertainties due to the modelling of MGRO J1908+06 and the contamination from Galactic diffuse emission are ±20% and −10% (−20%) for the east (west) hotspot, respectively, and are discussed in previous sections.

The detector response is estimated using Monte Carlo simulations and then cross-calibrated using an Crab Nebula18,21 source. The Crab Nebula18,21 is located ≈3° to the east of the HAWC data. Systematic uncertainties that potentially affect the result presented here include the charge resolution and relative quantum efficiency of the PMTs, the absolute quantum efficiency of the PMTs, changes to the detector layout as...
construction proceeded, uncertainties in the point spread function, and systematic differences in the distribution of arrival times of photoelectrons between data and simulation. The total systematic uncertainty on the flux normalization from detector effects is ±50%.

All the components of the systematic uncertainties are summarized in Extended Data Table 3 and combined in quadrature to estimate the total systematic uncertainty on the VHE flux from w1 and e1. We note that since the systematic uncertainties due to MGRO J1908−06 and GDE are anti-correlated, the quadrature sum overestimates the total systematic uncertainty. However, the effect is not particularly important, since the detector systematic effects are the dominant source of uncertainty.

**X-ray template fit and upper limit on the extent of the emission regions.** We performed several maximum likelihood fits modelling the hotspots as spatially extended sources. In the first fit, we generated spatial templates for the eastern and western regions based on the X-ray contours published by ROSAT and then performed a joint likelihood fit with the two γ-ray hotspots and MGRO J1908+06. This produces no improvement in TS over a point-source fit.

To constrain the size of the γ-ray emission regions, likelihood fits are applied using a Gaussian morphology convolved with the point spread function of HAWC. To reduce the number of free parameters, we first fitted MGRO J1908+06 using an ROI with SS 433 and its hotspots excluded. The extended fit from MGRO J1908+06 is then subtracted from the data, and the residual γ-ray emission from the γ-ray hotspots is fitted using two Gaussian functions. The centres of the Gaussians are fixed to e1 and w1, and their angular widths are estimated in a simultaneous fit to both the eastern and western regions.

The maximum likelihood fit yields an angular width of 0.14 ± 0.06 degrees for the east hotspot and 0.06±0.14 degrees for the west hotspot. We estimate the 90% confidence region on the extent as the value of Gaussian width that produces a decrease AS = −2.71 from the maximum likelihood value. The resulting 90% upper limits are 0.25° for the east region and 0.35° for the west region.

**Upper limit on emission from the central binary.** In the present dataset, no statistically significant emission is observed from the centre of SS 433. Using Feldman–Cousins likelihood ordering, we estimate the 90% upper limit on the flux at 20 TeV to be 5.3 × 10⁻⁶ TeV−1 cm⁻² s⁻¹ after fitting MGRO J1908+06 and the emission at e1 and w1.

**Upper limit on detected γ-ray energy.** The binning of γ-ray events into size bins B causes us to lose information about the energies of the γ-rays observed from SS 433. To determine the upper energy bound on the flux we observe, we scan over the maximum energy E_max used in the forward-folding analysis. Starting at E_max = 15 TeV, we find that TS increases monotonically until E_max = 25 TeV. Increasing E_max above this value causes TS to plateau (for e1) or decrease slightly (w1). We infer that the current measurement of e1 and w1 implies a maximum E_max = 25 TeV, and report this as a conservative estimate of the highest energy observed.

**Study of residual emission in the region of interest.** As a final check of the quality of the maximum likelihood fits, we plot the distribution of the significance values in each HEALPix pixel in the ROI around SS 433 in Extended Data Fig. 2. The significance values are plotted in units of Gaussian σ in each HEALPix pixel in the ROI around SS 433 in Extended Data Fig. 2. The hard X-ray data points and the sub-teraelectronvolt upper limits are set by the RXTE, MAGIC, H.E.S.S., and VERITAS observations of the e1 region<ref>18,19,20</ref>.

The VHE flux is determined using the flux from e1 at 20 TeV reported in Extended Data Table 1, where separate fits were made to eastern and western hotspots, and the positions were fixed to e1 and w1. The best-fit values of the injection spectrum and magnetic field in the emission region are α = 1.87 ± 0.04 ± 0.07, log[E_max (PeV)] = 3.53 ± 0.13 and field strength B = 16.0 ± 2.6 ± 2.1 G. Taking the distance to the source to be 5.5 kpc, the fit suggests a total electron energy of 2.9 × 10⁶⁴ erg. This is a small fraction of the total energy deposited by the jets of SS 433 over their lifetime, which is about 9 × 10⁶⁰ erg assuming a kinetic jet luminosity of 10⁶⁷ erg s⁻¹. Future multiwavelength observations dedicated to the VHE γ-ray emission region will better constrain the magnetic field strength and the properties of the electron population.

We note that the presence of several hundred teraelectronvolt–petaelectron-volt electrons would challenge the current particle acceleration mechanisms. Successful acceleration requires that the acceleration rate γ = eB/m_e c², where e is the charge of the electron and m_e is the electron mass, based on heuristic considerations (where v is the velocity associated with the notional electromotive force) exceed the cooling rate γ = 4κ c²/π² (B²/π³)/(3m_e c³), assuming that synchrotron radiation dominates the cooling processes in the lobes of SS 433. This leads to a maximum electron energy E_max = 271 TeV (v/100 km s⁻¹)⁻¹/₂ (B/16 G)⁻¹/₂. For reference, the Alfvén speed in the lobes is v_A = 160 km s⁻¹ (m_e/0.05 cm⁻³)⁻¹/₂ (B/16 G). A higher Alfvén speed could be achieved if the acceleration takes place in the central spine of the jet, where the mass loading due to black hole accretion is smaller and the magnetic field is stronger. Depending on the exact electron acceleration mechanisms, v could be associated with the jet flow velocity, or with the Alfvén speed. In both cases, using these estimates, it is possible that the maximum electron energy could exceed 1 PeV. However, the timescale of acceleration mechanisms such as second-order Fermi acceleration is related to the Alfvén time (v/A²), making the production of such high-energy electron-positron pairs less efficient. Future VHE γ-ray and hard X-ray observations can better constrain the electron cutoff energy, and diagnose the in situ particle acceleration mechanism.

**VHE emission due to hadronic interactions.** In the hadronic scenario, high-energy protons interact with the ambient gas in the source, and produce γ-rays via the decay π⁰ → γγ. Extended Data Fig. 3 shows the fraction of jet power that needs to be converted to protons to produce the observed γ-ray flux. We assume a proton spectrum dN/dE_p ∝ E_p⁻α exp(−E_p/E_max), and adopt a proton–proton interaction cross-section of around 50 mb, and a baryon density of 0.01–0.1 cm⁻³. The total proton energy is obtained by integrating this spectrum normalized to the VHE γ-ray flux.

If the diffusion coefficient in the source is comparable to that in the ISM, no hadronic models would be allowed, because they would require a proton injection rate that exceeds the total kinetic luminosity of the jets of SS 433. Even in extreme circumstances, for example, where the diffusion coefficient is extremely small, possibly owing to scattering by turbulence generated from the streaming cosmic rays, particles could remain in the jet as long as the jet lifetime of around 10⁹ years. Assuming that protons follow a hard spectrum with α < 2, the hadronic scenario would still require that at least 30% of the jet power goes to protons. Although a hadronic origin to the VHE flux is possible, it requires rather extreme source parameters and is therefore disfavoured.

**Code availability.** The study was carried out using the Analysis and Event Reconstruction Integrated Likelihood Fitting Framework (AERIE-LiFF) developed by the HAWC Collaboration. The software is open-source and publicly available on GitHub: https://github.com/rjlauer/aerie-liff. The code distribution includes instructions on installation and usage.

**Data availability**

The datasets analysed during this study are available at a public repository maintained by the HAWC Collaboration: https://data.hawc-observatory.org/.
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Extended Data Fig. 1 | VHE $\gamma$ rays from MGRO J1908+06 and SS 433/W50. The colour scale indicates the statistical significance of the excess counts above the background of contaminating cosmic rays and $\gamma$-rays before accounting for statistical trials. The bright extended $\gamma$-ray source MGRO J1908+06 is shown at the centre of the left panel with SS 433/W50 at the bottom. The dark contours show X-ray emission from SS 433 and its jets\textsuperscript{41}. The semicircular area indicates the region of interest used to fit the $\gamma$-ray observations. The right panel shows the $\gamma$-ray excess measured after the fitting and subtraction of $\gamma$-rays from the spatially extended source MGRO J1908+06. The dashed box indicates the region shown in Fig. 1. The jet termination regions e1, e2, e3, w1 and w2 observed in the X-ray data are indicated, as well as the location of the central binary.
Extended Data Fig. 2 | Distribution of pixel significance in the region of interest of the fit. The significance is defined as deviations from the background expectation, in the HAWC sky map (left panel), after fitting and subtraction of emission from MGRO J1908+06 (middle panel), and after fitting and removal of emission from MGRO J1908+06 and the $\gamma$ rays from w1 and e1 (right panel).
Extended Data Fig. 3 | Fraction of jet power needed to produce the observed VHE $\gamma$-rays in the hadronic scenario. The blue-shaded region shows the energy injection rate of protons, in units of the kinetic luminosity of the jet, required to produce the observed VHE $\gamma$-rays by interacting with ambient gas, as a function of the proton confinement time. A gas density of 0.05 cm$^{-3}$ is adopted for the source vicinity$^{16,27}$. Most hadronic models require $>100\%$ jet power (above the red solid line) and are thus not allowed. Even when the diffusion coefficient is extremely small (for reference, the dashed grey lines show the source age and the confinement time of 200 TeV protons in a 30-pc region in the ISM with Kraichnan- and Kolmogorov-type diffusion) and when the spectral index is much harder than 2, the hadronic scenario still requires a large energy input from the jet.
Extended Data Table 1  |  Fits to teraelectronvolt emission from SS 433 using nested point source models

| Lobe          | Position (RA, Dec) | $dN/dE$ at 20 TeV [$10^{-16}$ TeV$^{-1}$cm$^{-2}$s$^{-1}$] | TS  | Significance (post-trials) |
|---------------|--------------------|----------------------------------------------------------|-----|----------------------------|
| **Simultaneous fit to E+W hotspots, positions fixed.** |                    |                                                          |     |                            |
| E             | 19:13:37           | $2.4^{+0.6+1.3}_{-0.5+1.3}$                              | 41.2| $5.4\sigma$                |
|               | 04°55′48″          |                                                          |     |                            |
| W             | 19:10:37           | $2.1^{+0.6+1.2}_{-0.5-1.2}$                              |     |                            |
|               | 05°02′13″          |                                                          |     |                            |
| **Separate fit to E+W hotspots, positions fixed.** |                    |                                                          |     |                            |
| E             | 19:13:37           | $2.5^{+0.7+1.4}_{-0.5-1.4}$                              | 24.3| $4.6\sigma$                |
|               | 04°55′48″          |                                                          |     |                            |
| W             | 19:10:37           | $2.3^{+0.7+1.3}_{-0.5-1.3}$                              | 20.4| $4.2\sigma$                |
|               | 05°02′13″          |                                                          |     |                            |
| **Separate fit to E+W hotspots, positions floated.** |                    |                                                          |     |                            |
| E             | 19: 14: 11°20′26″  | $2.6^{+0.6+1.4}_{-0.5-1.4}$                              | 26.9| $4.4\sigma$                |
|               | 04°59′10″          |                                                          |     |                            |
|               | +03°30′26″         |                                                          |     |                            |
| W             | 19: 10: 40°17′58″  | $2.4^{+0.6+1.3}_{-0.5-1.3}$                              | 23.4| $4.0\sigma$                |
|               | 05°03′40″          |                                                          |     |                            |
|               | +03°32′17″         |                                                          |     |                            |

$dN/dE$ is the γ-ray flux, RA, right ascension; Dec., declination. TS, test statistic.
Extended Data Table 2  |  Dependence of measured HAWC flux at 20 TeV on spectral assumption, assuming a power law in energy parameterized by a spectral index and an exponential cutoff parameterized by $E_{\text{cutoff}}$

| $E_{\text{cutoff}}$ | East Lobe | West Lobe | East Lobe | West Lobe | East Lobe | West Lobe |
|---------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| No cutoff           | $1.0^{+0.3}_{-0.2}$ | $0.9^{+0.3}_{-0.2}$ | $2.4^{+0.6}_{-0.5}$ | $2.1^{+0.6}_{-0.5}$ | $3.3^{+0.9}_{-0.7}$ | $2.4^{+0.9}_{-0.6}$ |
| 50 TeV              | $4.7^{+1.1}_{-0.9}$  | $4.2^{+1.1}_{-0.9}$  | $5.0^{+1.2}_{-1.0}$  | $4.1^{+1.3}_{-0.9}$  | $3.2^{+0.9}_{-0.7}$  | $1.7^{+1.1}_{-0.7}$  |
| 300 TeV             | $1.7^{+0.5}_{-0.4}$  | $1.6^{+0.5}_{-0.4}$  | $3.3^{+0.8}_{-0.7}$  | $2.9^{+0.8}_{-0.7}$  | $3.6^{+0.9}_{-0.7}$  | $2.4^{+0.9}_{-0.7}$  |

$dN/dE$ at 20 TeV [×10^{-16} TeV^{-1} cm^{-2} s^{-1}]
Extended Data Table 3 | Systematic uncertainties on the flux of VHE $\gamma$-rays from SS 433 measured by HAWC

| Systematic                          | East Lobe | West Lobe |
|-------------------------------------|-----------|-----------|
| Detector Systematic Effects         | $\pm 50\%$ |           |
| MGRO J1908+06 Modeling              | $< \pm 20\%$ |           |
| Galactic Diffuse Contamination     | $-10\%$   | $-20\%$   |
| Total                               | $\pm 55\%$ | $\pm 55\%$ |