Gamma-ray heartbeat powered by the microquasar SS 433

Jian Li1✉, Diego F. Torres1,2,3,4, Ruo-Yu Liu5,6, Matthew Kerr7, Emma de Oña Wilhelmi1,2 and Yang Su6,8

Microquasars, the local siblings of extragalactic quasars, are binary systems comprising a compact object and a companion star. By accreting matter from their companions, microquasars launch powerful winds and jets, influencing the interstellar environment around them. Steady gamma-ray emission is expected to rise from their central objects, or from interactions between their outflows and the surrounding medium. The latter prediction was recently confirmed with the detection of SS 433 at high (TeV) energies1. In this report, we analyse more than ten years of gigaelectronvolt gamma-ray data from the Fermi Gamma-ray Space Telescope on this source. Detailed scrutiny of the data reveal emission in the vicinity of SS 433, co-spatial with a gas enhancement, and hints of emission possibly associated with a terminal lobe of one of the jets. Both gamma-ray excesses are relatively far from the central binary, and the former shows evidence of a periodic variation at the precessional period of SS 433, linking it with the microquasar. This result challenges obvious interpretations and is unexpected from previously published theoretical models. It provides us with a chance to unveil the particle transport from SS 433 and to probe the structure of the magnetic field in its vicinity.

SS 433 is a unique Galactic microquasar containing a compact object, most probably a black hole of ~10–20 solar masses (M⊙) orbiting an ~30M⊙ A3-7 supergiant star with an orbital period of 13.082 days (ref.7). The rate of mass transfer from the companion is determined from analysis of optical lines1 and is thought to be as high as 10−4M⊙yr−1, which is orders of magnitude larger than the Eddington limit. This steady supercritical accretion state powers highly collimated jets of plasma and mass-loaded non-polar outflows at a similar level15, with kinetic powers exceeding ~1039 erg s−1. The jets seem to inflate the W50 nebula surrounding SS 433 (ref.1), and perhaps also the H i shell-like structure seen on an even larger scale1. Jets and outflows in SS 433 eject matter at relativistic speeds, ~0.2c (refs.16,17), while precessing with a period of 162.250 days (ref.17). This timing signature is explained by the periodic pull of the giant secondary star, moving both the accretion disk and its outflows simultaneously. Doppler shifts of H and He lines in the optical band, as well as of highly ionized Fe lines in the X-ray band, indicate relativistic baryon content in the jets18, whereas knots seen at radio frequency indicate the existence of relativistic electrons19. Synchrotron emission in radio and X-ray bands is observed from the jet termination lobes18,20. Very-high-energy gamma-rays (>25 TeV) were also observed at these positions by the High-Altitude Water Cherenkov Observatory (HAWC), with a likely origin of inverse-Compton scattering between locally accelerated electrons and cosmic microwave background radiation1.

Gigaelectroml volt emission would also be expected from the same leptonic processes at the lobes of SS 433, although at a level that would be challenging to detect with the Fermi-Large Area Telescope (LAT). Nonetheless, the existence of baryons in the jets has also promoted models in which gamma-ray emission can rise hadronically at the jet base (see, for example, ref.17) and/or in interactions between molecular clouds and cosmic rays that diffuse away from the accelerating region (for example, ref.17).

Searches for gigaelectro n volt emission from the SS 433 region have thus been a subject of great interest, and a number of studies using Fermi-LAT data have been published in the past few years reporting on the source detection11–13 and extension14,15, or claiming to detect a hint of precessional periodicity16. However, these studies arrived at inconsistent conclusions and, as we detail in the Methods, they lacked a proper treatment for the contamination produced from nearby sources—in particular from the pulsar PSR J1907+0602—and are thus at risk of systematic biases. Using 10.5 years of Fermi-LAT data, we searched for gamma-ray emission related to SS 433 in the 100 MeV–300 GeV band during the off-peak phase of PSR J1907+0602. We detected two gigaelectronvolt excesses near SS 433, neither at the position of the central compact object. These excesses are shown in Fig. 1a, together with the radio morphology of the W50 nebula and X-ray contours of the lobes. There is a giga electronvolt excess (hereafter referred to as Fermi J1913+0515, at right ascension (RA) = 288.28°±0.04°, declination (dec) = 5.27°±0.04°) that lies adjacent to the X-ray contours of the east lobe of SS 433 but does not overlap them. Fermi J1913+0515 is spatially consistent with the Fermi-LAT 8-year Point Source List (FL8Y) gamma-ray source FL8Y J1913.3+0515. No gamma-ray source is found at this location in the Fermi-LAT Fourth Source Catalog (4FGL; see Methods). Assuming a power-law spectral shape, Fermi J1913+0515 is detected with a test statistic (TS) value of 39 (notionally 5.9σ) and a spectral index of 2.39±0.10stat±0.05sys, yielding an energy flux of (1.25±0.24stat±0.39sys)×10−11 erg cm−2 s−1 (where subscripts stat and sys correspond to the statistical and systematic errors), corresponding to a luminosity of 3.2×1034 erg s−1 (d = 4.6 kpc; ref.15). No morphological extension or spectral cutoff can be identified (see Methods).

The gigaelectro nvolt excess in the west is spatially coincident with the west lobe of SS 433, and is located at RA = 287.46°±0.09°,
dec = 4.98° ± 0.08°. Assuming a power-law spectral shape, the likelihood analysis of the excess results in a TS value of 15 (notionally 3.5σ), which is below the formal source detection threshold (TS = 25, see Methods). This dim west excess has a spectral index of 2.30 ± 0.16_{stat} ± 0.11_{sys} and an energy flux of (0.75 ± 0.25_{stat} ± 0.41_{sys}) × 10^{-11} erg cm^{-2} s^{-1}.

In an attempt to explore whether these excesses are linked to SS 433, we produced exposure-corrected, weighted 1 day light curves (Fig. 2). The Lomb–Scargle power spectra for Fermi J1913+0515 (a), the west excess (b) and PSR J1907+0602 (c) show a significant hint of the precessional period, which is confirmed by likelihood analysis.

Fig. 1 | Gamma-ray and atomic cloud images of the SS 433 region.
a. Fermi-LAT map of the SS 433 region in 0.1–300 GeV band during the off-peak phase of PSR J1907+0602. Background sources have been modelled and subtracted (see Methods). The colour scale shows the TS value, the square root of which gives an approximate detection significance.
b. Map of the Arecibo H_i emission integrated in the interval 65–82 km s^{-1} (colour scale). The image has been scaled by sin b (b is Galactic latitude) to enhance the features far from the Galactic plane. The 95% confidence level circle of the positions of Fermi J1913+0515 and the west excess are shown in green. The white contours show the radio continuum emission from the Effelsberg 11 cm survey from 300 mK and increase in intervals of 200 mK. Cyan contours show the smoothed X-ray images measured by ROSAT in the 0.9–2 keV band from 5 × 10^{-5} counts s^{-1} to 2 × 10^{-4} counts s^{-1} with intervals of 1.67 × 10^{-5} counts s^{-1} (see Methods). 10 pc scale bars at the distance of SS 433/W50 are shown in the bottom right corners.

Fig. 2 | SS 433 precession signal seen in Fermi J1913+0515.
a–c, Exposure-corrected Lomb–Scargle power spectra constructed from the 1–300 GeV weighted light curve of Fermi J1913+0515 (a), the west excess (b) and PSR J1907+0602 (c). The red dotted and dashed lines indicate false alarm probabilities of 1% and 5%. Only Fermi J1913+0515 shows a significant hint of the detection of the precessional period, which is confirmed by likelihood analysis.
above 1 GeV (see Methods) and searched for timing signals at the orbital and precessional period. Using Lomb–Scargle timing analysis, a hint of a periodic signal at 160.88±2.66 days is detected from Fermi J1913+0515 with a single-frequency significance of 3.6σ and a false alarm probability of 3.7×10⁻³ (see Methods). This period is consistent with the jet precession period of 162.250 days (Fig. 2). Neither the west excess nor other sources in the vicinity show the same periodicity, and none of the sources indicate variability at the orbital period. Fermi J1913+0515 itself is significantly detected, with a TS value of 31 (5.2σ) above 1 GeV. Thus, guided by the hint of precessional variability, we carried out a likelihood analysis in two broad precession phases (0.0–0.5 and 0.5–1.0 above 1 GeV), adopting the SS 433 ephemeris of reference (T₀ (JD) = 2443508.4098, see Methods)¹⁰. The difference is marked: Fermi J1913+0515 is significantly detected in the precession phase interval 0.0–0.5 with a TS value of 39 (5.9σ) and not detected at all in the precession phase interval 0.5–1.0, yielding a TS value of 3 (1σ, Fig. 3a). The precessional phase light curve is shown in Fig. 3b. Through likelihood analysis, we see that the flux in the precessional phase interval 0.0–0.5 is significantly higher than that in precession phase interval 0.5–1.0 at the 4.2σ level. The fluxes between the two precessional phase intervals significantly deviate from a constant at a 3.5σ level (see Methods).

The locations of Fermi J1913+0515 and the west excess nearby SS 433 reported here argue for possible physical connections. On the one hand, the 95% confidence level position circle of the west excess covers the X-ray excess¹³ and is close to the recent multi-teraelectronvolt source detected by HAWC, for which a leptonic, locally- accelerated origin was energetically preferred¹. On the other hand, the adjacent position, 160.88±2.66-day timing signal and related flux variability link Fermi J1913+0515 to the microquasar SS 433. However, this connection poses a significant interpretation challenge: which is the mechanism powering the gigaelectronvolt emission? How is this periodic signal generated?

Detectable gamma-ray signals from SS 433 and other microquasars have been predicted in the past, even at a roughly compatible level to the sources described here¹²,¹³,¹⁴. Moreover, owing to the precessional period of SS 433, a periodicity in the emission of gigaelectronvolt photons has also been predicted¹¹. This signal was proposed to originate in the periodically varying—synchronously...
with the precessional movement—gamma-ray absorption due to interactions with matter (via γN) and fields (via γγ processes) of the disk and the star[41]. In this scenario, the dominant gamma-ray production channel is hadronic, and emission must happen at the very base of the jets, at sufficiently high ambient densities that pp interactions can proceed. The latest H.E.S.S. and MAGIC upper limits[40] on the central source would require that the fractional power carried by relativistic protons in the SS 433 jets be ≤10−3. However, owing to the significant positional offset between the predicted and the detected source (~35 pc away from the central source, at a distance of ~4.6 kpc; ref. 29), we can conclude that the periodicity reported for Fermi J1913+0515 cannot be related to such gamma-ray absorption.

Coincident in position with Fermi J1913+0515 and at the consistent distance as SS 433, there is a gas enhancement beyond the diffuse average (Fig. 1b). The gas excess is located within a projected region of R_g ≈ 20 pc, with a mass that can reach up to M ≈ 250,000 M⊙ (see Methods). Assuming a spherical region of radius R_g, the average density is n ≈ 22 cm−3, although can be lower if the mass is more extended perpendicularly to the plane of the sky.

Direct periodic illumination of such region by the eastern jet seems unlikely. On the one hand, the coherence of the radio jet seems to be sustained on the arcsecond scale only[42]. Simulations confirm that the jet loses the helical morphology after a few precession cycles, due to the interaction with the surrounding medium[43,44]. On the other hand, Fermi J1913+0515 is not located within the extrapolated jet cone.

The interaction of protons accelerated in the central region of microquasars or at the jet termination in neighbouring clouds has been studied in the past[45]. In such scenarios, protons diffuse from their injection point and produce hadronic gamma-rays when they encounter appropriate targets. The average level of the gamma-ray flux that we measure from Fermi J1913+0515 can be accommodated in this setting. This scenario, however, can hardly explain the periodicity. Even assuming a periodic, impulsive injection of cosmic rays containing most of the jet energy released in a single period, these injections would not be energetically relevant individually, providing a cosmic-ray density subdominant to the Galactic sea. Further details of these considerations are given in the Methods.

An alternative possibility for proton injection could be the relativistic equatorial outflow recently characterized by NuSTAR[35]. This outflow has a more favourable geometry with respect to the gas enhancement. The line-of-sight outflow velocity is 0.14–0.29c (potentially higher if we are not viewing along the direction of the outflow), and it even exceeds the velocities seen in the approaching jet ejecta at any precessional phase[45]. Energetically, the outflow is as powerful as that of the jet and is believed to precess in solidarity with the jet and the accretion disc. The screening of the central source by these outflows would explain why SS 433 is not as X-ray bright as the 10−7 M⊙ yr−1 accretion rate would indicate[44]. However, and similarly to what was noted above, for proton interactions to be associated with the precessional periodicity, protons should arrive at a cloud periodically at a sufficient rate to produce the gamma-ray emission level seen. The periodic variability is thus intriguing, and difficult to reconcile with our current understanding of the source environment under common lore interpretations (the Methods provides further discussion).

SS 433 continues to amaze observers at all frequencies and theoreticians alike, and is certain to provide a testbed for our ideas on cosmic-ray production and propagation near microquasars for years to come.

**Methods**

**Details of the Fermi-LAT data analysis.** The analysis shown in this paper uses 10.5 years of Fermi-LAT data, from 2008 August 4 (MJD 54682) to 2019 January 28 (MJD 58511). We have considered all events with reconstructed energies between 100 MeV and 300 GeV and positions within a circular region of interest of 15° radius centred on PSR J1907+0602. We selected photons of the ‘Pass 8’ event class, using the 11.07-00 release of Fermi Science Tools.

We have used the P8R3 V2 Source instrument response functions, adopting a 0.1° angular threshold of <90° to eliminate contaminating gamma-rays from the Earth’s limb. A spectral–spatial model was constructed from the 4FGL[28]. Both Galactic (gll_iem_v07.fits) and isotropic diffuse emission components (iso_p8r3_source_v2_v1.txt) and known gamma-ray sources within 20° of PSR J1907+0602 were included.

The spectral parameters of the sources within 4° of our target were left free, whereas those of other (further) sources included were fixed at the 4FGL values. The spectral analysis was performed using a binned maximum likelihood fit (spatial bin size 0.1°, AIT projection and 30 logarithmically spaced bins in the 0.1–300 GeV range) with the Science Tool glkfit. The significance of the sources were evaluated using the TS. This statistic is defined as TS = −2ln(LMax/Lnull), where LMax is the maximum likelihood value for a model in which the source is studied (null hypothesis) and Lnull is the corresponding maximum likelihood value with this source being incorporated. The larger the value of TS, the less likely it is that the null hypothesis (no source) is correct, and that instead a significant gamma-ray excess lies at the tested position. For nested models and degenerate parameters, TS is approximately equal to the detection significance in terms of σ of a given source. A TS of 25 is adopted as the detection threshold in this paper, as is similarly done in the LAT source catalogues[28,43].

The extension significance was defined as TSext = −2ln(Lmax/Lnull), where Lext and Lnull are the gllkfit global likelihood of the extended source hypotheses and the point source hypothesis, respectively. A threshold for claiming a TS of 4σ (or 5σ) is set as TSext > 16, which corresponds to a significance of ~4σ.

The FermiPy python package (version 0.17.4)[46] was used to produce the TS maps and source localizations in this paper. An energy dispersion correction has been applied in the analysis.

The systematic errors have been estimated following standard procedures, that is, repeating the analysis using modified instrument response functions[37] that bracket the effective area and artificially changing the normalization of the Galactic diffuse model by ±6% (ref. 31). The latter dominates the systematic errors. In this paper, the first (second) uncertainty shown corresponds to the statistical (systematic) error.

**Pulsar contamination and the need of gating.** PSR J1907+0602 is a bright gamma-ray pulsar located only 1.4° away from SS 433. The photons from PSR J1907+0602 dominate the emission of the SS 433 region (Extended Data Fig. 1), up to the point that Fermi J1913+0515 is not visible in the counts map. To produce the pulse profile, we selected photons from PSR J1907+0602 above 300 MeV within a radius of 0.6°, selections that maximized the -test statistic[37,38]. The pulsation from PSR J1907+0602 is significantly detected with an H-test value of 14.948 (m = 20, where m is the number of harmonics for the H test). Its pulse profile is shown in Extended Data Fig. 1b.

To check for the level of contamination at the SS 433 region that may be produced by PSR J1907+0602, we extracted photons above 100 MeV within a radius of 0.6° centred on SS 433 (the dashed circle in Extended Data Fig. 1a), thus covering both regions of interest for this work: Fermi J1913+0515 and the west excess. Pulsar rotational phases for each gamma-ray photon were calculated at that position using the ephemeris of the pulsar PSR J1907+0602. The folded profile is shown in Extended Data Fig. 1c. It shows that the pulsation of PSR J1907+0602 is significantly recovered at the position of interest, with an H-test value of 418 (m = 11, above 8σ).

This exercise demonstrates that a non-gated analysis of the gamma-ray photons at the position of SS 433 is severely contaminated by PSR J1907+0602.

Another way to confirm the contamination level is to analyse gllkfit results for this dataset. The likelihood analysis of the PSR J1907+0602 in the 100 MeV–300 GeV band yields a TS value of 22,142, whereas for Fermi J1913+0515 it yields a TS value of 54. We also produced model counts map of PSR J1907+0602 and the Fermi instrumental model with the likelihood analysis. At the position of Fermi J1913+0515, 24 photons are expected to come from Fermi J1913+0515. In turn, 25 photons are expected to come from PSR J1907+0602 at the same position of interest.

**Pulsar gating.** To minimize the contamination from the nearby pulsar, we carried out our data analysis during the off-peak phases of PSR J1907+0602, following similar analyses in refs. 41,42. To define the off-peak interval, we divided the data into 25 bins, each separated by 15° radius centred on PSR J1907+0602. During the off-peak phases of PSR J1907+0602, following the method described in refs. 30, 31 and known gamma-ray sources within 20° of PSR J1907+0602 were included.

**Off-peak analysis.** During the off-peak phases of PSR J1907+0602, and assuming a power-law spectral shape, Fermi J1913+0515 is detected with a TS value of
Differences between the use of FL8Y and 4FGL. We note that Fermi J1913+0515 is associated with FL8Y J1913+0515 but that no 4FGL source is reported at this position. This is also a result of a change in the diffuse model used in the 4FGL. Indeed, the FL8Y list has 5,523 sources whereas the 4FGL catalogue has 5,065 sources. The two catalogues used the same amount of data and software, but different interstellar emission model (gll_iem_v07 for FL8Y and gll_iem_v06 for 4FGL), different energy ranges (100 MeV–1 TeV for FL8Y and 50 MeV–1 TeV for 4FGL) and a different threshold for a curved spectral shape ($\Delta T S > 16$ for FL8Y and $\Delta T S > 9$ for 4FGL). The different interstellar emission model (higher at lower energies in the new model) used in each catalogue is the main reason for the disappearance of sources. As stated in the 4FGL paper, changing the Galactic diffuse emission model from gll_iem_v06 to gll_iem_v07, even without changing the analysis or the data, caused the number of sources detected to decrease by 10%. We carried out an analysis of 8 years of P8R3 data in 50 MeV–1 TeV without pulsar gating, which is the same time period and energy range used for 4FGL. Using 4FGL and another pulsar gating law (Fermi J1913+0515 is not significantly detected, with $TS < 19$, which is consistent with the absence of a corresponding source in this list. However, using the 4FGL with the previous version of Galactic diffuse emission model (gll_iem_v06), Fermi J1913+0515 is again significantly detected with $TS = 36$. We have also checked our off-peak analysis presented in this paper using the FL8Y catalogue with corresponding Galactic diffuse emission model gll_iem_v06. Both Fermi J1913+0515 and the west excess are significantly detected with $TS = 73$ and $TS = 34$, respectively. Finally, we note that above 1 GeV, the difference in results using FL8Y and 4FGL is minor and all the results included in this paper are consistent in both analyses.

Weighted light curve. Adopting the best-fit spectral–spatial model derived from the precessional phase–averaged analysis, we selected photons within a $3^\circ$ radius of SS 433 and calculated the probability that each event originated from Fermi J1913+0515 using gtsrcprob. For a better point spread function and less contamination from background sources, we only considered events above 1 GeV. Binning into 1-day intervals and correcting for the instrument exposure produced a light curve. We searched for the precessional periodic signal in the light curve between 145 and 175 days using the Lomb–Scargle periodogram method. Power spectra around the 162.250 day precession period were generated for the Fermi J1913+0515 exposure-corrected and exposure-uncorrected light curves using the Python package pyastro (version 3.2.1) and PyAstronomy (version 0.3.0). No significant periodic signal was discovered in the uncorrected light curve. However, after the exposure correction is applied, a 160.88 $\pm$ 2.66 day period is detected with a single-frequency significance of 3.68, consistent with the 162.250-day jet precession period. The single-frequency significance was estimated using PyAstronomy. The 'standard' normalization method in Astropy was used. To calculate the false alarm probability and estimate how likely it is that the timing signal we detected had an origin in noise, we implemented a bootstrap method.

To construct the simulated light curve, we kept the temporal coordinates the same as the actual light curve and assumed a Gaussian white noise for the flux. We computed Lomb–Scargle periodograms on 100 resampled, simulated light curves and derived the false alarm probability of the detected timing signal at our period of interest. All the sampled periods in the Lomb–Scargle periodogram have been considered in the bootstrap. Our results are shown in Fig. 2.

The Lomb–Scargle timing analysis has also been checked with different binning (for example 5 days, 7 days, 10 days) of the weighted light curve. The results are all consistent and do not depend on the weighted light curve binning.

In addition, we note that the Fourier period resolution ($P = 2T$, where $P$ is the trial period and $T$ is the observation interval) of our 10.5-year light curve at $T = 160$ days is $\pm 3.4$ days. To infer the best period, the Fourier period resolution is usually oversampled by a factor of several, see for example, ref. 18. To obtain the results above, we oversampled it by a factor of $\sim 4$, leading to a period resolution of $0.08$ days around 160 days. However, the evidence for the periodic signal at 160.88 $\pm$ 2.66 days does not depend on the period resolution adopted in the Lomb–Scargle periodogram: other period resolutions around 160 days (for example $\sim 1.0$, $\sim 1.6$, and $\sim 3.4$ days—that is, with no oversampling) have been tested and all led to consistent results.

Using the same light curve and a similar method, a search for the 13.082-day orbital periodic signal was carried out between 10 and 20 days, leading to no detections.

The Lomb–Scargle timing analyses presented in this paper are not blind searches but were aimed instead at a small range around known periods, to reduce the number of periods sampled. As a check, we show the Lomb–Scargle periodogram covering the entire period range of the observation data in Extended Data Fig. 3. Besides the 160.88 $\pm$ 2.66 day periodic signal we reported in this paper, there is a peak around 93 days that is a temporal effect of the Fermi-LAT observation strategy. The broad structure between 400 and 600 days does not associate with any known period and similar structures could be reproduced in periodograms of simulated pure white noise. Considering the large number of periods sampled in the entire period range, all of the above timing structures are insignificant, being below the 5% false alarm probability level (red dashed line in Extended Data Fig. 3).

Likelihood analysis of the flux variation between precession phase 0.0–0.5 and 0.5–1.0. We adopted the precession period of 162.250 days from ref. 18. $T_0$ is set to the time of the largest separation of the moving emission lines in SS 433, JD 2443508.4098 (referred to as $T_0$ in refs. 16, 17). To estimate the significance of the flux variation between the precessional phase 0.0–0.5 and 0.5–1.0, derived in the main text, we employed a likelihood analysis in the 1–300 GeV band. The two datasets of precessional phase 0.0–0.5 and 0.5–1.0 are jointly fitted using summed likelihood analysis. An additional co-spatial source with Fermi J1913+0515 is added for precession phase 0.0–0.5 to model any flux excess from that in the precession phase 0.5–1.0. With spectral index fixed at the value of Fermi J1913+0515 independently derived in precessional phase 0.0–0.5, the co-spatial source yields a TS value of 18 ($\sim 4.2\sigma$), and further demonstrates the significance of the flux difference between the two precessional phases. To further explore the trend of flux modulation, we show the precession phase light curve of Fermi J1913+0515 in the 1–300 GeV band with a binning of 0.25 (Fig. 5).

To calculate the significance of the flux deviation from a constant between precessional phases 0.0–0.5 and 0.5–1.0, the two corresponding datasets were fitted simultaneously using summed likelihood analysis. The spectral index of Fermi J1913+0515 was fixed to the value derived from precessional phase–averaged data. The analysis was carried out first with the normalization of Fermi J1913+0515 tied together Galactic diffusional emitters, and then repeated with it untied. The $\Delta T S$ between two maximum log-likelihood values is 12, which corresponds to a significance of $3.5\sigma$ and is consistent with the timing signal. The binning in the precessional phase, that is, 0–0.5 and 0.5–1.0, is arbitrary and adopted a priori on the basis of the ephemeris. Thus, only one trial is introduced in the analysis. Because of the lower exposure during precessional phase 0.5–1.0, the corresponding uncertainties in the individual flux measurements grow, see Fig. 3. However, as the Fig. 3 shows, we tested a posteriori that the coarse variability trend is maintained even at smaller bins (for example, even dividing the precessional phase in 10 bins, Extended Data Fig. 4).

As a consistency check, we carried out the same timing and precessional phase–related likelihood analysis in the 0.1–1 GeV band. No significant periodic signal is detected and no flux variation can be claimed. The $\Delta T S$ between maximum log-likelihood values of precessional phases 0.0–0.5 and 0.5–1.0 is 1.6.

The same check was further carried out above 1 GeV for the full dataset, that is, without pulsar gating of PSR J1907+0602. A weak hint of a periodic signal at 162.5 days ($\sim 2.9^\circ$ days) is detected from Fermi J1913+0515, with a single-frequency significance of 2.7$\sigma$. The $\Delta T S$ between maximum log-likelihood values of precessional phases 0.0–0.5 and 0.5–1.0 is 8, indicating a flux deviation from a constant at 2.8$\sigma$. The decreased significance of timing and flux variation is most probably due to the larger number of events that originate in PSR J1907+0602; its Poissonian flux fluctuation will smear the periodic flux variation from Fermi J1913+0515, which is much dimmer in comparison.

Stability of the timing signal. We also carried out a cumulative likelihood analysis during the precession phases 0.0–0.5 and 0.5–1.0 in the 1–300 GeV band. To allow for significant measurements along the evolution, we adopted a step of eight precession periods and show the evolution of the $\Delta T S$ versus the trial period in Extended Data Fig. 5a. The TS of Fermi J1913+0515 during the precessional phase 0.0–0.5 increases as observation time accumulates, whereas it stays almost unchanged during precessional phase 0.5–1.0. As a result, the flux difference between the two precessional phases becomes more significant, providing additional credibility to the timing signal reported. To explore further the stability of the timing signal,
Neutral atomic gas analysis. To compare the gamma-ray emission of SS 433 with the large-scale gas in the region, we used the 21 cm emission line of H I as a tracer of the neutral atomic gas. The Galactic ALFA HI (GALFA-LO) survey data from the Arecibo Observatory 305 m-telescope was investigated. These data were first used in the report by ref. 5. The GALFA HI cube data have a grid spacing of 1 arcmin and a velocity channel separation of 0.184 km s\(^{-1}\). Typical noise levels are 0.1 K rms of brightness temperature in an integrated velocity of 1 km s\(^{-1}\).

Based on the data in Table 2, an enhancement of atomic gas excess coincident with Fermi J1913+0515 at V\(_{21}\) cm of 66.8 km s\(^{-1}\), which corresponds to a distance of \(\sqrt{\frac{4}{\pi} \cdot 0.7 \text{ kpc}}\), consistent with that of SS 433\(\alpha\). The enhancement is located at RA = 288.11\(^\circ\), dec = 5.31\(^\circ\) with a radius of \(\sim 15\) arcmin (\(\sim 20\) pc at 4.6 kpc). The H I intensity of the main structure is \(\sim 1,000\) km s\(^{-1}\), leading to the total mass of \(\sim 250,000\) M\(_{\odot}\). The volume-averaged density of the H I gas enhancement is estimated to be \(\sim 22\) cm\(^{-3}\), assuming a spherical region of radius \(R_c\). Given the relatively large grid spacing of the observations, the H I gas enhancement could be located in clumps or in a central cusp. The existence of clumps has often been found when clouds are observed at higher resolution in our Galaxy and beyond\(\beta\). However, the low average density makes strong clumpiness, albeit in principle possible, unlikely\(\gamma\).

Gigaelectronvolt emission due to hadronic interactions? To assess whether the gigaelectronvolt emission could be due to hadronic interactions, we considered a numerical solution of the (isotropic) diffusion equation—from an injection point up to a given distance—to compute the cosmic-ray density. We then used the latter to compute the gamma-ray emission (similarly to procedures used in refs. \(\delta\)–\(\epsilon\)).

Provided that the interstellar cosmic-ray proton energy density in the region of SS 433 is the same as the locally detected density, we find that either in a continuous conversion of a fraction of the jet kinetic luminosity to cosmic rays, or in an impulsive cosmic-ray injection event of much shorter duration than the age of the jets, assumed here to be \(\sim 2 \times 10^8\) years, as in (for example) ref. \(\zeta\) (albeit the argument would not be significantly changed in this case this age is smaller, see ref. \(\zeta\)), the cosmic-ray density at the cloud could exceed the Galactic sea, generating gamma-rays against the averaged proton density at a comparable level of flux to that detected. The average level of gamma-ray flux we measure from Fermi J1913+0515 is equivalent to a luminosity \(L_p = 10^{41}\) erg s\(^{-1}\) at the distance of SS 433. To accommodate this luminosity via hadronic interactions, we need a total energy of cosmic-ray protons interacting with the atomic cloud as \(W_p = 2.5 \times 10^{41}\) (\((L/10^{41}\text{ erg s}^{-1})/0.01\text{ cm}^{-3}\)) ergs. Protons might be accelerated at the terminal lobe, or come from the SS 433 equatorial outflow, and reach Fermi J1913+0515 through isotropic diffusion. The distances from east termination lobe or from the SS 433 central object to Fermi J1913+0515 are similar (see Fig. 1). The kinetic power of both the jet and the equatorial outflow are also similar (\(\sim 10^{41}\) erg s\(^{-1}\); ref. \(\zeta\)). Thus, in either scenario an accumulation of proton injection over \(\sim 100\) yr is needed to supply the required proton energy and, consequently, any periodical signal due to injection will be smeared out.

Even if it is assumed that a sufficient cosmic-ray energy is injected in each single period to accommodate the observed gamma-ray flux, the difference in the arrival times to the cloud of cosmic rays between two consecutive injection events separated by a precessional period is small in comparison to the precessional period itself, such that many injections would still accumulate in the cloud, erasing the period signal produced by the arrival of fresh protons.

This situation is quantitatively exemplified in Extended Data Fig. 6, where we are purposely considering a period of \(\sim 20\) times longer than the precessional period of SS 433 so that each individual instantaneous injection both contains a larger amount of energy (equal to the kinetic power released in the period) and is more numerically tractable (given the need to consider only \(100\) periods to cover a significant age \(\sim 22,000\) years). To maximize the cosmic-ray luminosity at the cloud, this example will also purposely consider a high total luminosity of \(3 \times 10^{41}\) erg s\(^{-1}\), of which \(20\%\) is assumed to end in cosmic rays at the injection point. We assume that the latter propagate isotropically in a medium with diffusion coefficient of \(10^{28}\) cm\(^2\) s\(^{-1}\); we tested that changes in the latter will not modify conclusions. Extended Data Fig. 6a shows the contributions to 10 GeV cosmic rays (an example of an energy relevant for producing 1 GeV photons) at different distances from the injection point (around the separation between the cloud and SS 433) of 100 individual injection events, compared with the Galactic cosmic-ray sea (represented by the horizontal line). At intermediate times, each injection event can provide \(\sim 10^4\) GeV cosmic rays than the Galactic sea. Note that this would not be the case should the real precessional period of SS 433 be considered (500 times smaller), that is, the individual injections would be subordinate to the Galactic sea in that case, although the general scenario would hold. Extended Data Fig. 6b shows the cosmic-ray density (at all energies); the green lines represent individual injection event (corresponding to \(10, 20, 30\ldots 100\) in the x axis of Extended Data Fig. 6a), whereas the violet line shows the sum of the contribution of all injection events. Similarly, Extended Data Fig. 6c shows the hadronic gamma-ray emission at 1 GeV (obtained from a computation of a full spectral energy distribution, with the corresponding proton density) at different distances. To exemplify this further, we considered how the gigaelectronvolt gamma-ray flux evolves in time in the scenario described if an injection of \(\sim 22,000\) yr. Again, we consider an impulsive periodical injection of cosmic rays and isotropic diffusion, but here we use the real jet precessional period 162,250 days. The cloud is located 35 pc away from the cosmic-ray injection point. For typical ISM diffusion coefficients (that is, \(D = 10^{26}\) cm\(^2\) s\(^{-1}\)), we cannot see any hint of the periodicity in gamma-ray flux, with a complete loss of the injection memory. We also examine the influence of the diffusion coefficient. A larger diffusion coefficient would, in principle, help to reveal the periodicity.

However, we still cannot find any periodicity even with \(D = 10^{26}\) cm\(^2\) s\(^{-1}\). To focus on the temporal behaviour, we normalize the fluxes in employed diffusion coefficients to the fluxes in the cloud for the same period. The resulting gamma-ray flux decreases with increasing diffusion coefficient. So even if a larger diffusion coefficient, with which the periodicity can be present, is somehow achieved, it would lead to an energy budget crisis to power the observed gamma-ray flux. Thus, this approach would be unable to explain the periodicity.

There are two ways of conceptually alleviating this situation. One could consider that the cosmic-ray sea is a central cusp. The existence of clumps has often been found when clouds are observed at higher resolution in our Galaxy and beyond. However, the low average density makes strong clumpiness, albeit in principle possible, unlikely. The other possibility is that the jet injection is not constant, or the magnetic field is not fixed in space. This would yield a smeared out periodicity. However, to have a magnetic field, with which the periodicity can be present, is somehow achieved, it would lead to an energy budget crisis to power the observed gamma-ray flux. Thus, this approach would be unable to explain the periodicity.

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**Author contributions**

J.L. led the observational analysis. J.L. and D.F.T. wrote the manuscript together, iterating on all aspects of the analysis, their interpretation and modelling. R.-Y.L. contributed to the theoretical interpretations. M.K. provided the timing ephemeris of gamma-ray pulsar PSR J1907+0602. E.d.O.W. participated in the interpretation of the results. Y.S. provided analysis and input for the neutral atomic gas. All authors discussed the contents of the paper and contributed to the preparation of the manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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Correspondence and requests for materials should be addressed to J.L.

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Extended Data Fig. 1 | Gamma-ray pulsar PSR J1907+0602's contamination on SS 433 region. 

a, 100 MeV – 300 GeV counts map of the Fermi-LAT field of the SS 433 region. The microquasar itself is noted with a bold cross. The fitted position of Fermi J1913+0515 and west excess are shown with green crosses. The regions used to produce pulse profiles are shown with dotted circles. 

b, Folded pulse profile of PSR J1907+0602 above 300 MeV with an ROI of 0.6°. Two rotational pulse periods are shown, with a resolution of 100 phase bins per period. The Bayesian block decomposition is shown by red lines. The off-peak interval ($\phi = 0.697–1.136$) is defined by black dotted lines. 

c, Folded pulse profile of the photons centered on SS 433 with a radius of 0.6° above 100 MeV, using the ephemeris of PSR J1907+0602. Two rotational pulse periods are shown, with a resolution of 25 phase bins per period. The vertical error bar in (b) and (c) indicates the 68% credible interval.
Extended Data Fig. 2 | Gamma-ray spectra of Fermi J1913+0515 and the west excess. a, b, Fermi-LAT spectra of Fermi J1913+0515 (a) and the west excess (b). The maximum likelihood model (power law) fitted with gtlike is shown with a dashed line. The vertical error bar indicates the 68% credible interval and the upper limits are at the 99% confidence level.
Extended Data Fig. 3 | Full period range timing analysis of Fermi J1913+0515. Exposure-corrected Lomb-Scargle power spectra constructed from the 1–300 GeV weighted light curve of Fermi J1913+0515 covering the entire period range of the observation data (top panel, 0–700 days; bottom panel, 700–3800 days). The red dashed line indicates false alarm probability of 5% level corresponding to the full period range power spectra.
Extended Data Fig. 4 | Precessional phase light curves of Fermi J1913+0515. Precessional phase light curve of Fermi J1913+0515 flux (top panel) and TS values (bottom panel) in 1-300 GeV with a binning of 0.1. The vertical error bar indicates the 68% credible interval and the upper limits are at the 95% confidence level.
Extended Data Fig. 5 | Stability of the timing signal. a, cumulative likelihood analysis during precession phase 0.0–0.5 and 0.5–1.0. The TS of Fermi J1913+0515 in precession phase 0.0–0.5 and 0.5–1.0 are shown with blue squares and red triangles. The ΔTS of the flux deviation from a constant are shown with black dots. The TS of the flux difference between two precessional phase bins are shown with green stars. b, 2D plane contour plotting for the WWZ power spectrum.
Extended Data Fig. 6 | Examples of simulations for a periodic, instantaneous injection of protons. a, the contributions to 10 GeV cosmic rays at different distances from the injection point of 100 individual injection events, compared to the Galactic cosmic-ray sea (the black horizontal line). Each symbol/color represents a different distance (30, 35, 40, 45 and 50 pc) from injection to the interaction point. b, the cosmic-ray density at all energies. The green lines represent individual injection event (corresponding to 10, 20, 30... 100 in the x-axis of (a)), whereas the violet line shows the sum of the contribution of all injection events. c, the hadronic gamma-ray emission at 1 GeV at different distances. Symbol/color representations are the same with (a).