LETTERS

Discovery of very-high-energy γ-rays from the Galactic Centre ridge

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The source of Galactic cosmic rays (with energies up to 10^{15} eV) remains unclear, although it is widely believed that they originate in the shock waves of expanding supernova remnants[1,2]. At present the best way to investigate their acceleration and propagation is by observing the γ-rays produced when cosmic rays interact with interstellar gas[3]. Here we report observations of an extended region of very-high-energy (>10^{11} eV) γ-ray emission correlated spatially with a complex of giant molecular clouds in the central 200 parsecs of the Milky Way. The hardness of the γ-ray spectrum and the conditions in those molecular clouds indicate that the cosmic rays giving rise to the γ-rays are likely to be protons and nuclei rather than electrons. The energy associated with the cosmic rays could have come from a single supernova explosion around 10^4 years ago.

The observations described here were carried out with the High Energy Stereoscopic System (HESS), a system of four imaging atmospheric-Cherenkov telescopes[4]. The instrument operates in the teraelectronvolt energy range (TeV), beyond the regime accessible to satellite-based detectors (MeV up to ~10 GeV). At satellite energies, the technique of probing the distribution of cosmic rays using γ-ray emission has been demonstrated in the large-scale mapping of the Galactic plane by EGRET[5]. The γ-ray flux was found to approximately trace the density of interstellar gas, illustrating that the flux of cosmic rays is roughly constant throughout the Galaxy. However, given its modest angular resolution (~1°), EGRET could only resolve the few nearest molecular clouds. The order-of-magnitude better angular resolution of HESS opens up this possibility of resolving individual clouds out to the distance of the Galactic Centre. Moreover, in the energy range accessible to EGRET, the picture is complicated owing to three comparable contributions to the diffuse γ-ray flux (from cosmic ray electrons[1] via inverse Compton scattering and Bremsstrahlung radiation and from cosmic ray protons via neutral pion decay). In the energy range of HESS the dominant component of the truly diffuse γ-ray emission is very probably the decay of neutral pions produced in the interactions of cosmic rays with ambient material. Taken together, the wide field of view (~5°) and the improved angular resolution (better than 0.1°) of HESS have made possible the mapping of extended γ-ray emission.

Early HESS observations of the Galactic Centre region led to the detection of a point-like source of very-high-energy (VHE) γ-rays at the gravitational centre of the Galaxy (HESS J1745−290) (ref. 6), compatible with the positions of the supermassive black hole Sagittarius A*, the supernova remnant Sagittarius A East, and a Galactic Centre source reported by other groups[7,8]. A more sensitive exposure of the region in 2004 revealed a second source: the supernova remnant/pulsar wind nebula G0.9+0.1 (ref. 9). These two sources are clearly visible in Fig. 1a. For previous VHE instruments such sources were close to the limit of detectability. With the greater sensitivity of the HESS instrument it is possible to subtract these two sources and search for much fainter emission. Subtracting the best-fit

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model for point-like emission at the position of these excesses yields the map shown in Fig. 1b. Two significant features are apparent after subtraction: extended emission spatially coincident with the unidentified EGRET source 3EG J1744−3011 (discussed in ref. 10) and emission extending along the Galactic plane for roughly 2°. The latter emission is not only very clearly extended in longitude l, but also significantly extended in latitude b (beyond the angular resolution of HESS) with a characteristic root-mean-square (r.m.s.) width of 0.2°, as can be seen in the Galactic latitude slices shown in Fig. 2. The reconstructed γ-ray spectrum for the region $|l| < 0.8°$, $|b| < 0.3°$ (with point-source emission subtracted) is well described by a power law with photon index $\Gamma = 2.29 \pm 0.07_{\rm stat} \pm 0.20_{\rm sys}$ (Fig. 3; see the Supplementary Information for a discussion of systematic errors).

Given the plausible assumption that the γ-ray emission takes place near the centre of the Galaxy, at a distance of about 8.5 kpc, the observed r.m.s. extension in latitude of 0.2° corresponds to a scale of ~30 pc. This value is similar to that of interstellar material in giant

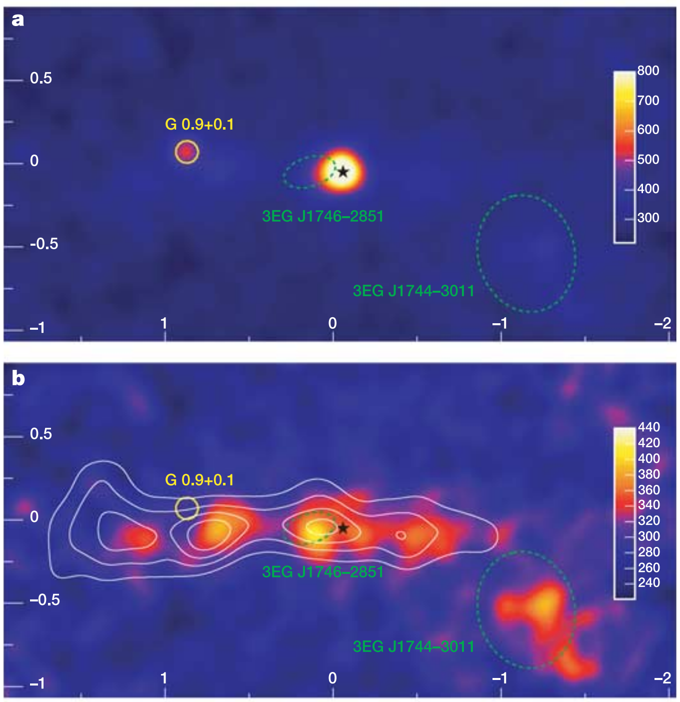

Figure 1 | VHE γ-ray images of the Galactic Centre region. a, γ-ray count map; **b**, the same map after subtraction of the two dominant point sources, showing an extended band of gamma-ray emission. Axes are Galactic latitude (x) and Galactic longitude (y), units are degrees. The colour scale is in 'events' and is dimensionless. White contour lines indicate the density of molecular gas, traced by its CS emission. The position and size of the composite supernova remnant G0.9+0.1 is shown with a yellow circle. The position of Sgr A* is marked with a black star. The 95% confidence region for the positions of the two unidentified EGRET sources in the region are shown as dashed green ellipses[20]. These smoothed and acceptance-corrected images are derived from 55 hours of data consisting of dedicated observations of Sgr A*, G0.9+0.1 and a part of the data of the HESS Galactic plane survey[21]. The excess observed along the Galactic plane consists of ~3,500 γ-ray photons and has a statistical significance of 14.6 standard deviations. The absence of any residual emission at the position of the point-like γ-ray source G0.9+0.1 demonstrates the validity of the subtraction technique. The energy threshold of the maps is 380 GeV, owing to the tight γ-ray selection cuts applied here to improve signal/noise and angular resolution. We note that the ability of HESS to map extended γ-ray emission has been demonstrated for the shell-type supernova remnants RXJ1713.7–3946 (ref. 22) and RX J0852.0−4622 (ref. 23). The white contours are evenly spaced and show velocity integrated CS line emission from ref. 11, and have been smoothed to match the angular resolution of HESS.

molecular clouds in this region, as traced by their CO emission and in particular by their CS emission[11]. CS line emission does not suffer from the problem of 'standard' CO lines[12]: that clouds are optically thick for these lines and hence the total mass of clouds may be underestimated. The CS data suggest that the central region of the Galaxy, $|l| < 1.5°$ and $|b| < 0.25°$, contains about $3\text{–}8 \times 10^7$ solar masses of interstellar gas, structured in a number of overlapping clouds, which provide an efficient target for the nucleonic cosmic rays permeating these clouds. The region over which the γ-ray spectrum is integrated contains 55% of the CS emission corresponding to a mass of $1.7\text{–}4.4 \times 10^7$ solar masses. At least for $|l| < 1°$, we find a close match between the distribution of the VHE γ-ray emission and the density of dense interstellar gas as traced by CS emission (Fig. 1b and Fig. 2).

The close correlation between γ-ray emission and available target material in the central 200 pc of our galaxy is a strong indication for an origin of this emission in the interactions of cosmic rays. Following this interpretation, the similarity in the distributions of CS line and VHE γ-ray emission implies a rather uniform CR density in the region. In the case of a power-law energy distribution the spectral index of the γ-rays closely traces the spectral index of the cosmic rays themselves (corrections due to scaling violations in the cosmic-ray interactions are small, $\Delta\Gamma < 0.1$; see Supplementary Information), so the measured γ-ray spectrum implies a cosmic-ray spectrum near the Galactic Centre with a spectral index close to 2.3, significantly harder than in the solar neighbourhood (where an index of 2.75 is measured). Given the probable proximity of particle accelerators, propagation effects are likely to be less pronounced than in the Galaxy as a whole, providing a natural explanation for the harder spectrum which is closer to the intrinsic cosmic-ray-source spectra. The main uncertainty in estimating the flux of cosmic rays in the Galactic Centre is the uncertainty in the amount of target material. Following ref. 3 and using the mass estimate of ref. 11 we can estimate the expected γ-ray flux from the region, assuming for the moment that the Galactic Centre cosmic-ray flux and spectrum are identical to those measured in the solar neighbourhood. Figure 3 shows the expected γ-ray flux as a grey band, together with the observed spectrum. While below 500 GeV there is reasonable agreement with this simple prediction, there are clearly more high-energy γ-rays than expected. The γ-ray flux above 1 TeV is a factor of 3–9 higher than the expected flux. The implication is that the number density of cosmic rays with multi-TeV energies exceeds the local density by the same factor. The size of the enhancement increases rapidly at energies above 1 TeV.

The observation of correlation between target material and TeV γ-ray emission is unique and provides a compelling case for an origin of the emission in the interactions of cosmic-ray nuclei. In addition, the harder-than-expected spectrum and the higher-than-expected TeV flux imply that there is an additional component to the Galactic Centre cosmic-ray population above the cosmic-ray 'sea' that fills the Galaxy. This is the first time that such direct evidence for recently accelerated (hadronic) cosmic rays in any part of our Galaxy has been found. The energy required to accelerate this additional component is estimated to be 10^{49} erg in the energy range 4–40 TeV or $\sim10^{50}$ erg in total if the measured spectrum extends from $10^9\text{–}10^{15}$ eV. Given a typical supernova explosion energy of 10^{51} erg, the observed cosmic ray excess could have been produced in a single supernova remnant, assuming a 10% efficiency for cosmic-ray acceleration. In such a scenario, any epoch of cosmic-ray production must have occurred in the recent enough past that the rays that were accelerated have not yet diffused out of the Galactic Centre region. Representing the diffusion of protons with energies of several TeV in the form $D = \eta \times 10^{30}\,{\rm cm^2\,s^{-1}}$ (where $10^{30}\,{\rm cm^2\,s^{-1}}$ is the approximate value of the diffusion coefficient in the Galactic disk at TeV energies), we estimate the diffusion timescale to be $t = R^2/2D \approx 3{,}000(\theta/1°)^2/\eta$ years, where θ is the angular distance from the Galactic Centre. Owing to the larger magnetic field and higher turbulence in the central region compared to more conventional regions of the Galactic disk, the normalization parameter η is probably ≤ 1 and a source or sources of age ~10 kyr could fill the region $|l| < 1°$ with cosmic rays. Indeed, the observation of a deficit in VHE emission at $l = 1.3°$ relative to the available target material (see Fig. 2) suggests that cosmic rays, which were recently accelerated in a source or sources in the Galactic Centre region, have not yet diffused out beyond $|l| = 1°$.

The observed morphology and spectrum of the γ-ray emission provide evidence that one or more cosmic-ray accelerators have been active in the Galactic Centre in the last 10,000 years. The fact that the diffuse emission exhibits a photon index Γ that is the same—within errors—as that of the central source HESS J1745−290 suggests that this object could be the source in question. Within the 1′ error box of HESS J1745−290 are two compelling candidates for such a cosmic-ray accelerator. The first is the supernova remnant Sgr A East (ref. 13) with its estimated age around 10 kyr (ref. 14); younger ages have been quoted for Sgr A East (ref. 15), reflecting the significant uncertainty in this estimate. The second is the supermassive black hole Sgr A* (refs 16, 17), which may have been more active in the past.

Another alternative possibility is that a population of electron accelerators produces the observed γ-ray emission via inverse Compton scattering. Extended objects with photon indices close to the value 2.3 observed in the Galactic Centre are observed elsewhere in the Galactic plane[10]. The parent population of objects such as pulsar wind nebulae (that is, massive stars) would probably approximately follow the distribution of molecular gas. However, in the intense photon fields and high magnetic fields within and close to the Galactic Centre molecular clouds[18,19], TeV electrons would lose their energy rapidly: $t_{\rm rad} \approx 120(B/100\,\mu{\rm G})^{-2}(E_{\rm e}/10\,{\rm TeV})^{-1}$ years. We would therefore expect to see rather compact sources (point-like

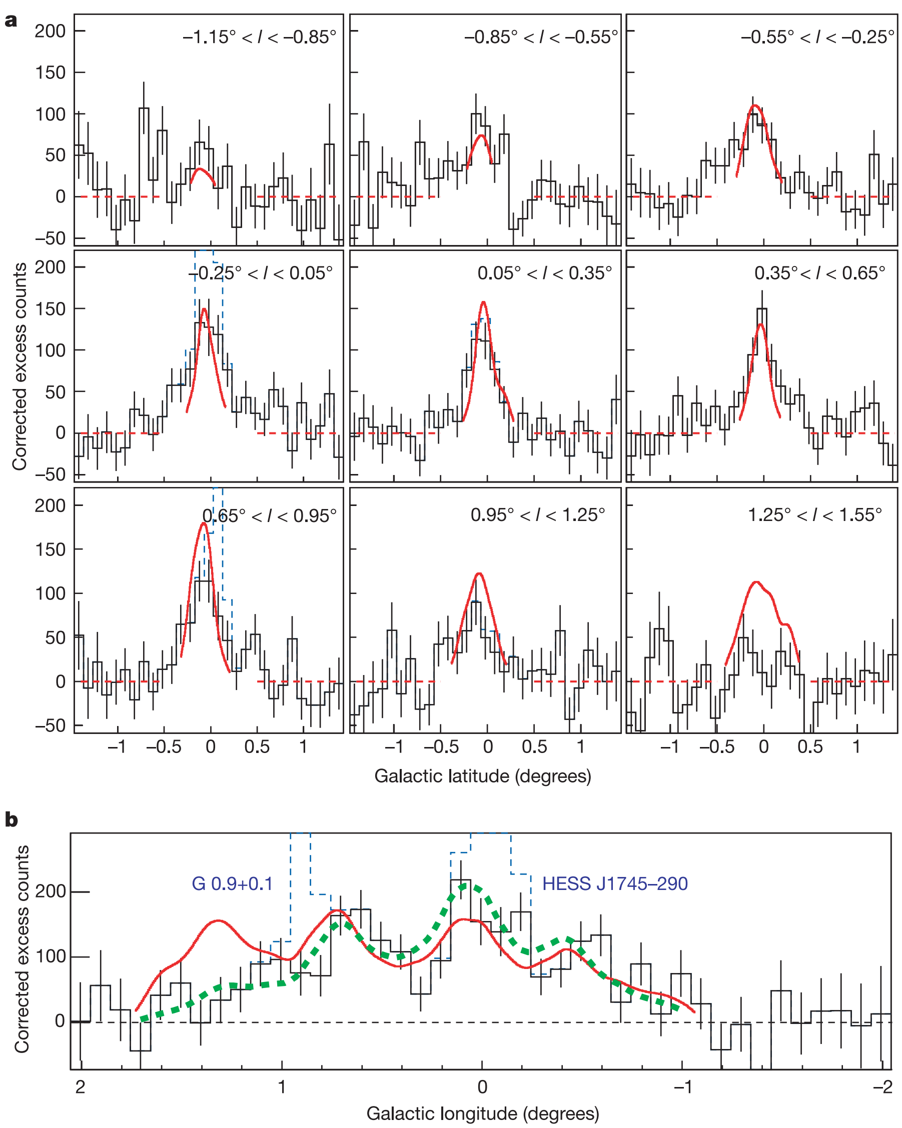

Figure 2 | γ-ray emission from the Galactic Centre region. Distribution of γ-ray emission in Galactic latitude (for individual slice in longitude, **a**) and in Galactic longitude (**b**). The red curves show the density of molecular gas, traced by CS emission. The upper panel shows acceptance-corrected (and cosmic-ray background-subtracted) γ-ray counts for 0.3°-wide bands in longitude. The point-source-subtracted counts are shown in black. The dashed blue histogram shows the unsubtracted values (the y scale is truncated). The red curves correspond to the smoothed CS map of Fig. 1 and are drawn only in the regions where CS measurements are available. The dashed red lines show nominal zero CS density in regions away from the Galactic plane. Panel **b** shows γ-ray counts versus l for $-0.2° < b < 0.2°$. The CS line flux may be underestimated close to $l = -1°$, owing to a narrower coverage in b at this longitude. The dashed line shows the γ-ray flux expected if the cosmic-ray density distribution can be described by a gaussian centred at $l = 0°$ and with r.m.s. 0.8°, as expected in a simple model for diffusion away from a central source of age ~10^4 years. In all plots the background level is estimated using events from the regions $0.8° < |b| < 1.5°$. Error bars show ±1 standard deviation.

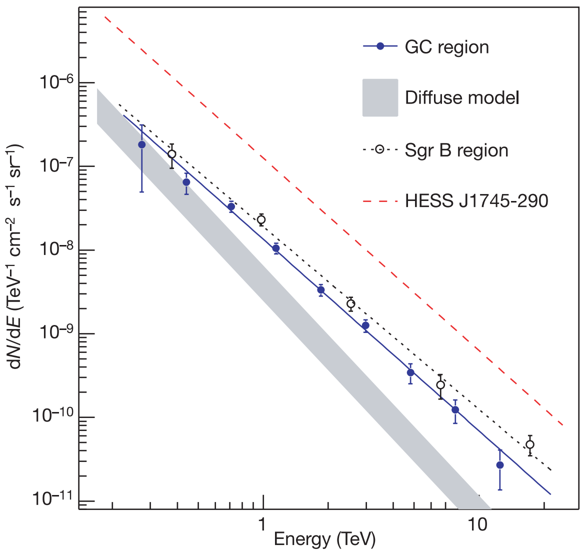

Figure 3 | Energy distribution of Galactic cosmic rays. γ-ray flux per unit angle in the Galactic Centre region (data points), compared with the expected flux, assuming a cosmic-ray spectrum as measured in the solar neighbourhood (shaded band). The spectrum of the region $|l| < 0.8°$, $|b| < 0.3°$ is shown using full circles. These data can be described by a power law: $dN/dE = k[E(\text{in TeV})]^{-\Gamma}$, with $k = (1.73 \pm 0.13_{stat} \pm 0.35_{sys}) \times 10^{-8}\ \text{TeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$ and a photon index $\Gamma = 2.29 \pm 0.07_{stat} \pm 0.02_{sys}$. The shaded box shows the range of expected π^0-decay fluxes from this region assuming a cosmic-ray spectrum identical to that found in the solar neighbourhood and a total mass of $1.7–4.4 \times 10^7$ solar masses in the region $|l| < 0.8°$, $|b| < 0.3°$ estimated from CS measurements. Above 1 TeV an enhancement by a factor of 3–9 relative to this prediction is observed. Using independent mass estimates derived from submillimetre measurements[24], $5.3 \pm 1.0 \times 10^7$ solar masses, and from $C^{18}O$ measurements[25], $3^{+2}_{-1} \times 10^7$ solar masses, results in enhancement factors of 4–6 and 5–13, respectively (see Supplementary Information). The strongest emission away from the bright central source HESS J1745–290 occurs close to the Sgr B complex of giant molecular clouds[26]. In a box covering this region ($0.3° < l < 0.8°$, $-0.3° < b < 0.2°$), integrated CS emission suggests a molecular target mass of $6–15 \times 10^6$ solar masses. The energy spectrum of this region is shown using open circles. The measured γ-ray flux (>1 TeV) implies a high-energy cosmic-ray density which is 4–10 times higher than the local value. Standard γ-ray selection cuts are applied here, yielding a spectral analysis threshold of 170 GeV. The spectrum of the central source HESS J1745−290 is shown for comparison (using an integration radius of 0.14°). All error bars show ±1 standard deviation.

for HESS) that would also be bright in the X-ray regime (as is, for example, G0.9+0.1). The existence of about ten such unknown sources in this small region again seems unlikely. Any substantially extended inverse Compton source would probably be a foreground source along the line of sight towards the Galactic Centre region, making any correlation with central molecular clouds entirely coincidental.

Received 13 July; accepted 22 November 2005.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of HESS is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme of the CNRS, the UK Particle Physics and Astronomy Research Council (PPARC), the IPNP of Charles University, the South African Department of Science and Technology and National Research Foundation, and by the University of Namibia. We would like to thank M. Tsuboi for providing the CS survey data used here and Y. Moriguchi and Y. Fukui for helpful discussions on molecular tracers.

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