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LETTERS

A connection between star formation activity and cosmic rays in the starburst galaxy M82

The VERITAS Collaboration*

Although Galactic cosmic rays (protons and nuclei) are widely believed to be mainly accelerated by the winds and supernovae of massive stars, definitive evidence of this origin remains elusive nearly a century after their discovery[1]. The active regions of starburst galaxies have exceptionally high rates of star formation, and their large size—more than 50 times the diameter of similar Galactic regions—uniquely enables reliable calorimetric measurements of their potentially high cosmic-ray density[2]. The cosmic rays produced in the formation, life and death of massive stars in these regions are expected to produce diffuse γ-ray emission through interactions with interstellar gas and radiation. M82, the prototype small starburst galaxy, is predicted[3,4] to be the brightest starburst galaxy in terms of γ-ray emission. Here we report the detection of >700-GeV γ-rays from M82. From these data we determine a cosmic-ray density of 250 eV cm^{-3} in the starburst core, which is about 500 times the average Galactic density. This links cosmic-ray acceleration to star formation activity, and suggests that supernovae and massive-star winds are the dominant accelerators.

M82 is a bright galaxy located approximately 12,000,000 light yr from Earth, in the direction of the Ursa Major constellation[5]. For hundreds of millions of years, M82 has been gravitationally interacting with nearby galaxies, including the larger spiral galaxy M81 (ref. 6). Over time, interactions with these neighbours have deformed M82, creating an active starburst region in its centre with a diameter of ~1,000 light yr (ref. 7). The NASA Hubble Space Telescope reveals hundreds of young, massive (10^4–10^6 solar masses) clusters in this starburst region[8]. Throughout this compact region, stars are being formed at a rate approximately ten times faster than in entire 'normal' galaxies like the Milky Way, and the supernovae rate is 0.1–0.3 yr^{-1} (refs 9, 10). The intense radio synchrotron emission observed in the central region of M82 suggests a very high cosmic-ray energy density, about two orders of magnitude higher than in the Milky Way[11]. The region also contains a high mean (molecular) gas density, of about 150 particles per cubic centimetre, or about 10^9 solar masses in total[12]. Given the high cosmic-ray and gas densities, M82 has long been viewed as a promising target for γ-ray observatories[7]. However, emission from it was not detected above 100 MeV by the NASA Energetic Gamma-Ray Experiment Telescope experiment[13], nor during previous very-high-energy (VHE, energy >100 GeV) γ-ray observations of M82 made using the Whipple 10-m Telescope[14] and by the High Energy Gamma Ray Astronomy[15] experiment. The latter two set upper limits on the flux from M82 at ~10% of that from the Crab Nebula, the brightest steady VHE source in the sky. These limits are well above the sensitivity of the Very Energetic Radiation Imaging Telescope Array System (VERITAS).

VERITAS[16] is located in southern Arizona and has been fully operational since September 2007. It consists of a stereoscopic array of four 12-m-diameter optical telescopes equipped with sensitive cameras (3.5° field of view) that detect short (~3-ns) flashes of ultraviolet and blue light known as Cherenkov radiation. This light is emitted in the electromagnetic cascade of secondary particles resulting from the interaction of a VHE γ-ray in the upper atmosphere. VERITAS has an energy threshold of ~100 GeV, an energy resolution of ~15% and an angular resolution of ~0.1° per event.

We observed M82 using VERITAS for a total of ~137 h of quality-selected live time between January 2008 and April 2009 at a mean zenith angle of 39°. This exceptionally long exposure was made entirely during periods of astronomical darkness and clear atmospheric conditions. The analysis of these data was performed according to the standard VERITAS analysis procedure[17] using event-selection criteria optimized a priori for low-flux, hard-spectrum sources. We observed an excess of 91 γ-ray-like events (~0.7 photons per hour) above the estimated background (267 events) from the direction of M82 (Supplementary Information). This excess corresponds to a post-trial statistical significance of 4.8σ, or a chance probability of 7.7×10^{-7}, and represents the discovery of VHE γ-ray emission from M82 (Fig. 1). The observed

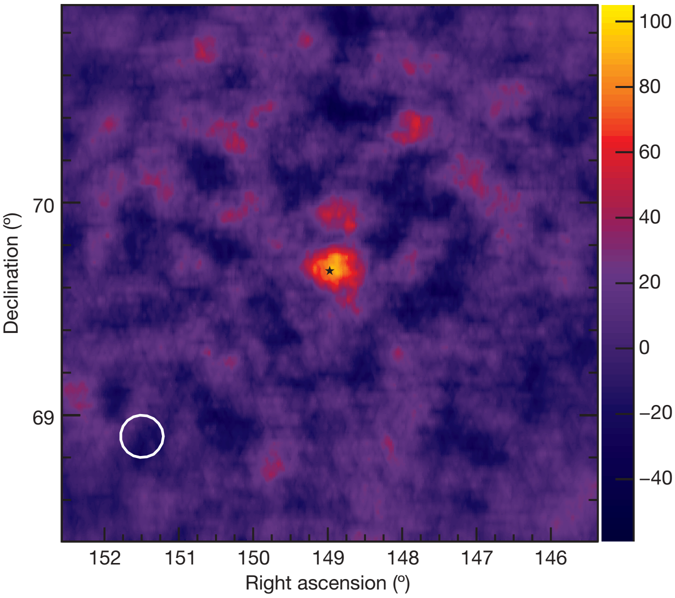

Figure 1 | VHE image of the M82 region. The sky map shows the measured excess (colour scale) of γ-ray-like events above the estimated background from a region centred on M82. Each pixel contains the excess in a circular region of radius 0.1°. The map is oversampled; neighbouring pixels are thus correlated. The background for each point is estimated using an annulus centred on its position (the ring method[28]). The spatial distribution of the observed excess is consistent with that expected from a point-like source located near the core of M82. The white circle represents the VERITAS point spread function (68% containment) for individual γ-rays. The uncertainty in the source localization is much smaller. The black star denotes the location of the core of M82. The coordinates are for the J2000 epoch.

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differential VHE γ-ray spectrum (Fig. 2) is best fitted using a power-law function with a photon index of $\Gamma = 2.5 \pm 0.6_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}}$ (the two uncertainties corresponding to statistical and systematic errors, respectively). The measured γ-ray flux is $(3.7 \pm 0.8_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above the 700-GeV energy threshold of the analysis, and no flux variations are observed. The luminosity of M82 above 700 GeV that we infer from the γ-ray flux is 2×10^{32} W, which is about 2×10^{6} times smaller than its far-infrared (100-μm) luminosity[18].

Having a flux of 0.9% of that observed from the Crab Nebula, M82 is among the weakest VHE sources ever detected. Although VERITAS has detected several confirmed VHE sources with flux values close to this, we performed a large number of tests to ensure that systematic effects could not potentially create a spurious signal in the data (Supplementary Information). None of these tests gave any indication that the observed signal is an artefact.

Before our discovery of VHE γ-ray emission from M82 using VERITAS, all known extragalactic VHE sources were clearly associated with an active galactic nucleus, an object powered by accretion onto a supermassive black hole. Although M82 may have a supermassive black hole at its centre, it exhibits at most only a weak level of activity that would point to its being an active galactic nucleus[19]. However, the high rate of star formation in M82 implies the presence of numerous strong shock waves in supernova remnants and around massive young stars. In the Milky Way, similar shock waves are known to accelerate electrons to very high energies, and they are suspected to similarly accelerate ions. This acceleration is expected to supply the cosmic rays that permeate both the Galaxy and M82, and which produce diffuse γ-ray emission.

The most recent theoretical models[2–4,7] predict a VHE γ-ray flux from M82 on the basis of the acceleration and propagation of cosmic rays in the starburst core. The various calculated fluxes are all close to the value measured by VERITAS. Using the model[3] shown in Fig. 2, from the VHE flux we estimate the cosmic-ray density in the starburst core of M82 to be ~250 eV cm^{-3}, which is approximately 500 times the average Milky Way density. Although the cosmic-ray density of the M82 core is significantly higher, the total cosmic-ray energy content of the two systems is similar because in terms of volume the Milky Way is about 500 times the larger. The lifetime of cosmic-ray particles in the M82 core is constrained to approximately 1,000,000 yr owing to energy losses through adiabatic cooling in the starburst wind and through collisions with interstellar gas nuclei. This is about 30 times shorter than the lifetime of the gigaelectronvolt-band particles in the Milky Way, which dominate the local cosmic-ray density. Thus, a correspondingly larger source power is needed to replenish these particles in M82 to maintain similar cosmic-ray energy content. Interestingly, the estimated supernova rate in M82 is about a factor of 30 larger than in the Milky Way. The VERITAS data therefore show an enhancement in the cosmic-ray acceleration that matches the enhancement in energy input by massive stars and supernovae. This correlation strongly supports the long-held theory that these objects have a dominant role in cosmic-ray production.

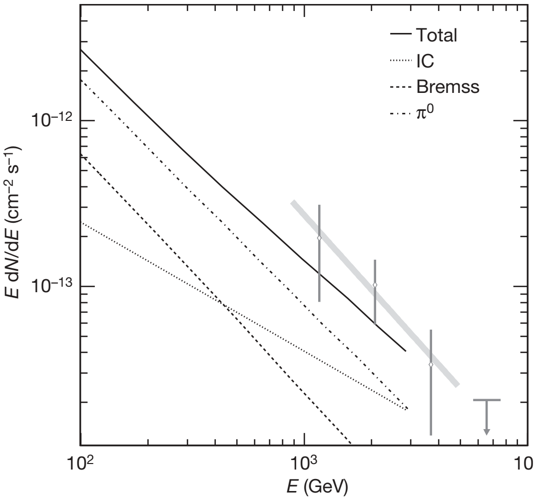

Figure 2 | Gamma-ray flux compared with a theoretical prediction. The differential energy spectrum ($E\mathrm{d}N/\mathrm{d}E$, where E denotes energy and N is the number of photons) of M82 observed using VERITAS between ~0.9 TeV and ~5 TeV. The data are given by open diamonds with 1σ statistical error bars, and can be fitted ($\chi^2 = 0.1$ with 1 d.f.) with a power-law function (thick grey line: $\mathrm{d}N/\mathrm{d}E \approx E^{-\Gamma}$, where E is measured in teraelectronvolts and $\Gamma = 2.5 \pm 0.6_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}}$). The VERITAS flux upper limit (99% confidence level[29]) shown at ~6.6 TeV is above the extrapolation of the fitted power-law function at these energies. The thin lines represent a recent model[3] for the γ-ray emission from M82. The thin solid line is the total emission predicted and the dashed lines represent components of this emission that result from the interactions of cosmic-ray ions with interstellar matter (decay of neutral pions (π^0)), from radiation from cosmic-ray electrons through inverse Compton scattering (IC) and from Bremsstrahlung radiation (Bremss). The IC and π^0 decay components are the dominant contributions of cosmic-ray electrons and ions, respectively. Notably, the spectral slopes of these dominant components are markedly different.

Although the VERITAS data strongly indicate that smaller shocks (for example those in supernova remnants) are the predominant cosmic-ray acceleration sites, it cannot be ruled out that this acceleration occurs on larger (>30-light-yr) scales in a more distributed fashion[1]. Significantly lower estimates of the M82 supernova rate[4] would also suggest other potential sources of cosmic-ray acceleration. However, alternative sources of mechanical energy for cosmic-ray acceleration, such as galactic rotation[1], can be ruled out.

The aforementioned theoretical models include significant contributions from both leptonic (for example electron) and hadronic (for example ion) particle interactions, which are expected to give different VHE γ-ray spectra (Fig. 2). Cosmic-ray ions create VHE γ-rays through collisions with interstellar matter. This process creates unstable particles called pi mesons (pions). Electrically neutral pions directly decay into γ-rays. Charged pions eventually decay into neutrinos and electrons. The latter emit synchrotron radiation in the radio and infrared bands through interactions with the ambient magnetic field. The radio emission from these secondary electrons can be used to place an upper limit on the γ-ray flux produced by cosmic-ray ions, thus helping to further discriminate between VHE γ-rays emitted by cosmic-ray ions and those coming from cosmic-ray electrons. The radio flux observed at a frequency of 32 GHz (ref. 20) implies that cosmic-ray ions would not produce a γ-ray flux at 20 GeV greater than about $2.5 \times 10^{-9}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, unless the magnetic field in M82 is considerably weaker than the conventional estimate, of 8 nT. An extrapolation of the VHE γ-ray spectrum measured with VERITAS using the fitted power-law index, $\Gamma = 2.5$, would exceed that limit by a factor of two, whereas an extrapolation with $\Gamma = 2.3$, which is within the uncertainty range of the fitted value, would satisfy the limit. The comparison suggests that either the true γ-ray spectrum between 10 GeV and 1 TeV is slightly harder (has a lower photon index) than our best-fit spectrum suggests, or the γ-ray emission does not come predominantly from cosmic-ray ions.

The observed radio emission may also come from the relativistic cosmic-ray electrons accelerated in M82. All electrons interact with ambient infrared photons, boosting them into the hard X-ray/soft γ-ray band by means of inverse Compton scattering. This non-thermal process contributes ~25% to the diffuse X-ray flux[21], the remainder of which originates from thermal emission of hot gas. Observational limits on the steady, non-thermal diffuse X-ray emission place its luminosity, at a photon energy of 5 keV, not significantly higher than the VHE γ-ray luminosity observed using VERITAS. These X-ray data provide a lower limit on the amplitude of the interstellar magnetic field that is about a third of the current estimate (8 nT) and, hence, an upper limit on the absolute number of relativistic cosmic-ray electrons in M82 with kinetic energies of ~1 GeV. Electrons of much higher kinetic energy (~10 TeV) are needed to produce VHE γ-rays through inverse Compton scattering of ambient infrared photons. Both theoretical considerations and a

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comparison of the observed VHE γ-ray flux with limits on the cosmic-ray-induced X-ray flux suggest that the inverse Compton emission should have a hard spectrum with a power-law index of $\sim$2 between 100 keV and 100 GeV. Because $>$100-GeV electrons quickly lose their energy by inverse Compton scattering and synchrotron emission, eventually preventing their further acceleration above a characteristic energy, the inverse Compton radiation spectrum should also steepen and eventually show a cut-off. The identification of a cut-off in this spectrum, potentially observable by combining data from VERITAS and the NASA Fermi Gamma-ray Space Telescope, could demonstrate which type of cosmic-ray particle is responsible for the VHE emission.

The VERITAS measurements of M82 also have implications for the interpretation of the striking correlation observed between the far-infrared emission (from warm dust) and the radio emission (from synchrotron radiation of cosmic-ray electrons) in starburst galaxies[22,23]. Massive-star formation is generally accepted as the origin of both[24], but consensus is lacking on how such a tight correlation is produced[25–27]. The VHE flux measured from M82 places these models on a sound footing by providing an independent estimate of the cosmic-ray density. The observed VHE flux also requires a hard cosmic-ray spectrum (scaling as the pth power of energy, with p between -2.1 and -2.3 (refs 3, 4)), which places new constraints on models of the radio/far infrared correlation.

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

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