Discovery of VHE Gamma-ray Emission from the Starburst Galaxy M82

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The galaxy M82 has long been considered a promising target for very-high-energy (VHE) gamma-ray observations because of the compact starburst region in its core. Theoretical predictions have suggested it should be detectable by ground-based imaging Cherenkov telescopes like VERITAS and that a detection would have implications for the understanding of the origin of cosmic rays. M82 was observed with the VERITAS array during the 2007-2009 observing seasons. With an exposure of 137 hours, VERITAS was able to detect a gamma-ray signal at the 5σ level. This marks the discovery of gamma rays not only from M82 but also from the new source class of starburst galaxies. The observed flux from M82 is $(3.7 \pm 0.8_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-13}$ photons cm$^{-2}$ s$^{-1}$ above an energy threshold of 700 GeV, which corresponds to 0.9% of the Crab Nebula flux. The differential energy spectrum is a power law with a photon index $\Gamma = 2.5 \pm 0.6_{\text{stat}} \pm 0.2_{\text{syst}}$. Both the flux and the photon index are close to recent theoretical predictions. The VERITAS data indicate a strong correlation between the star-formation activity and the cosmic-ray production in M82.

1. Introduction

The existence of cosmic rays near the Earth has been well established ever since their discovery in the early 20th century [1], but their origin has eluded us ever since. Although there are no direct measurements of cosmic rays beyond Earth, there are indirect observations which give strong evidence for cosmic rays permeating the entire Galaxy and most significantly in the Galactic plane. This comes from the diffuse gamma-ray emission seen by the Fermi Large Area Telescope (Fermi-LAT), interpreted as mainly coming from cosmic-ray ions interacting with interstellar gas producing neutral pions which subsequently decay into gamma rays, although there is also a contribution from cosmic-ray electrons upscattering ambient photons to gamma-ray energies.

The leading hypothesis is that winds and supernovae of massive stars provide the major acceleration sites of Galactic cosmic rays, and observations of supernova remnants, such as the shell-type supernova remnant RX J1713.7-3946 [2], are suggestive of this scenario. The detection of the Large Magellanic Cloud (LMC) with the Fermi-LAT [3] shows gamma-ray emission coincident with the star-forming region 30 Doradus in the LMC. If massive star winds and supernova remnants accelerate cosmic rays then star-forming regions like this should indeed be emitting gamma rays.

The bright galaxy M82 is located at a distance of about 3.4 Mpc in the direction of the constellation Ursa Major [4]. Ongoing interactions with nearby galaxies, including the spiral galaxy M81 (see [5]), have formed a compact active starburst region, about 1000 light yrs across, in the center of M82. In this region, stars are being formed at a rate approximately ten times faster than in an entire “normal” galaxy like the Milky Way and the rate of supernovae is 0.1-0.3 yr$^{-1}$ [6,7]. Observations of the central region of M82 at radio frequencies, interpreted as synchrotron radiation of cosmic-ray electrons spiraling in the galactic magnetic fields, suggest a very high cosmic-ray energy density, about two orders of magnitude higher than in the Milky Way [8]. The mean molecular gas density is also high, about 150 particles per cubic centimeter or about $10^{9}$ solar masses total in the starburst region [9].

Because of the aforementioned properties of the starburst core, M82 has long been considered a probable gamma-ray source. Neither the Energetic Gamma-Ray Experiment Telescope (EGRET) [10] onboard NASA’s Compton Gamma-Ray Observatory nor previous ground-based gamma-ray observatories, such as the Whipple 10m telescope [11], detected gamma-ray emission from M82. Upper limits on the gamma-ray flux were set by EGRET at 4.4 photons cm$^{-2}$ s$^{-1}$ for $E > 100$ MeV and by Whipple at about 10% of the flux from the Crab Nebula for $E > 100$ GeV. The latter limit is above the sensitivity of the Very Energetic Radiation Imaging Telescope Array System (VERITAS).

2. Observations and Analysis

VERITAS [12] is an array of four imaging atmospheric Cherenkov telescopes located at the basecamp of the Fred Lawrence Whipple Observatory near Tucson, Arizona. The array has been fully operational since mid-2007 and has the sensitivity to detect a point source with 1% of the steady Crab nebula flux in less than 50 hours [3]. Observations cover the energy

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1The integral flux sensitivity above 300 GeV was improved by about 30% with the move of one telescope in the summer of 2009, which corresponds to a decrease in the time required to
range from 100 GeV to beyond 30 TeV with an energy resolution of 15-20% above 300 GeV, and an angular resolution per gamma-ray photon of 0.1° at 1 TeV. The observations of M82 were made in the period between January 2008 and April 2009. The total exposure amounts to about 137 hours of quality-selected live time, i.e. time periods of astronomical darkness and clear sky conditions, which is the deepest exposure taken with VERITAS to date. By observing the source offset from the center of the field-of-view, simultaneous estimation of the background was made possible [13]. The source was observed at a mean zenith angle of 39°.

The data analysis was performed using the standard VERITAS analysis tools [14] using event-selection criteria that were optimized a priori for a low-flux hard-spectrum source. A total excess of 91 gamma-ray-like events (see the sky map in Figure 1) were detected above the estimated background (267 background events). The excess corresponds to a post-trials significance of 4.8σ. The observed gamma-ray flux above the 700 GeV energy threshold of the analysis is \((3.7 \pm 0.8_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-13} \text{ photons cm}^{-2} \text{ s}^{-1}\) and, as shown in the lightcurve in Figure 2, there are no flux variations. From the gamma-ray flux we infer the gamma-ray luminosity to be \(2 \times 10^{32} \text{ W}\), which is about \(2 \times 10^{6}\) times smaller than the measured far-infrared (100µm) luminosity [15]. The differential VHE gamma-ray spectrum (shown in Figure 3) is best fitted using a power-law function \(dN/dE \propto E^{-\Gamma}\) with a photon index of \(\Gamma = 2.5 \pm 0.6_{\text{stat}} \pm 0.2_{\text{syst}}\) (the two uncertainties corresponding to statistical and systematic errors respectively).

The VHE gamma-ray flux from M82 is 0.9% that observed from the Crab Nebula, which makes it one of the weakest gamma-ray sources ever detected. Because of the exceptionally long exposure, several tests were performed to ensure that systematic effects did not introduce a spurious signal in the data. The signal and the measured spectrum and flux have been verified with independent calibration and analysis chains. For further details see the supplementary information of [16].

3. Discussion

VERITAS has for the first time detected VHE gamma-ray emission from an extragalactic source that is not clearly associated with an active galactic nucleus (AGN), in which the emission of gamma rays is powered by accretion onto a supermassive black hole. It is possible that M82 harbors a supermassive black hole in its center but there is at most very weak signs of AGN activity [17].

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The observed VHE gamma-ray emission includes

contributions from both hadronic (protons and heav-
ier ions) and leptonic (electrons and positrons) in-
teraction channels. The spectra from these channels
are quite different in the VHE regime. Cosmic-ray
ions produce gamma rays in collisions with interstellar
gas. In these collisions, unstable secondary particles,
mostly pions, are produced which subsequently decay.
The electrically neutral pions decay directly into two
photons and the charged pions decay into neutrinos and
muons, which then decay into more neutrinos and
electrons or positrons. The latter can then in the pres-
ence of a magnetic field emit synchrotron radiation in
the radio or infrared bands.

If one assumes that the electron population is
strictly secondary electrons from the above mentioned
process, then an observation of the synchrotron radio
emission sets an upper limit on the gamma-ray flux
from cosmic-ray ions. The observations of M82 at 32
GHz frequency \cite{21} set the limit at $2 \times 10^{-9}$ photons
\text{cm}^{-2} \text{s}^{-1}$ at a photon energy of 20 GeV (assuming
the magnetic field is not much weaker than the current
estimate of 8 nT). This energy is below the detect-
capabilities of VERITAS, but an extrapolation
of the VERITAS spectrum ($\Gamma = 2.5$) to this energy
would exceed the limit by about a factor of two. This
means the spectrum at TeV energies has a slightly
lower photon index than the VERITAS best-fit spec-
trum or the gamma-ray emission is not predominantly
from cosmic-ray ions.

An alternative scenario is that the observed radio
emission comes from primary electrons accelerated in
the starburst region. These electrons would also in-

teract with ambient photon field and upscatter those
photons to hard X-ray and soft gamma-ray energies.
By observing the non-thermal X-ray emission it is
then possible to constrain the electron population.
Observations place the non-thermal X-ray luminosity
at 5 keV photon energy, not much higher than the ob-
erved VHE gamma-ray luminosity. The X-ray data
place a lower limit on the interstellar magnetic-field
strength at about a third of the current estimate of
8 nT. From this an upper limit on the absolute num-
ber of electrons with energies around 1 GeV can be
derived. Theoretical predictions suggest the gamma-
ray spectrum from Compton upscattering should be a
power law with a photon index of about 2 in the 100
keV to 100 GeV energy range. Electrons with ener-
gies higher than that will lose energy quickly, and the
acceleration efficiency is decreased at a characteristic
energy. This implies a cut-off should be introduced
in the spectrum and identification of such could help

the starburst region of M82 than in the entire Wilky
Way. The VERITAS detection of VHE gamma rays
from M82 shows a correlation between cosmic-ray ac-
celeration and massive-star formation and provides an
important piece in the effort to reveal the origin of
cosmic rays.

Figure 3: Differential energy spectrum $(E \times dN/dE,$
where $E$ is the gamma-ray energy and $N$ is the photon
count) of M82 measured with VERITAS (open diamonds
with 1\sigma error bars). The VERITAS points can be fitted
with a power-law function, $dN/dE \propto E^{-\Gamma},$ where
$\Gamma = 2.5 \pm 0.6_{\text{stat}} \pm 0.2_{\text{syst}},$ indicated by the thick grey
line. The flux upper limit at about 6.6 TeV is above the
extrapolation of the fitted power law at that energy. The
theoretical model prediction \cite{20}, of the total emission is
given by the thin solid line. Its components are from $\pi^0$
decays, inverse Compton scatterings and bremsstrahlung.
(Figure from \cite{16}.)

to accelerate cosmic rays. These cosmic rays perme-
ate the galaxy and produce gamma rays as they in-
teract with interstellar gas and photon fields. Recent
theoretical work \cite{18, 19, 20} has predicted the VHE
gamma-ray flux from M82 based on acceleration and
propagation models of cosmic rays in the starburst re-
gion and the galaxy. These authors all predict fluxes
close to that measured by VERITAS. In Figure 3 the
model of \cite{20} is compared with the VERITAS result.

The cosmic-ray density in the starburst core of M82
can be estimated using the observed VHE gamma-ray
flux. At about 250 eV cm$^{-3}$, the density is about 500
times larger than the average of the Milky Way. It
must be noted though, that the Milky Way is much
larger in terms of volume and thus the total energy in
cosmic rays is similar.

Because of various energy-loss mechanisms, such as
adiabatic cooling in the stellar winds and interactions
with interstellar gas, the lifetime of cosmic rays in M82
is of the order of 1 Myr. This is lower than the typical
lifetime of cosmic rays in the Milky Way by about a
factor of 30. In order to maintain the same level of
energy content in cosmic rays, the power input into
cosmic rays must be correspondingly higher. Interest-
ingly, the supernova rate is about 30 times higher in
identify the underlying gamma-ray production mechanism.

Recently, the Fermi-LAT team has reported on the detection of high-energy gamma rays from M82 [22]. Combination of data from VERITAS and Fermi-LAT will further help us understand the origin of cosmic rays.

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References

[1] Butt, Y. 2009, Nature, 460, 701
[2] Aharonian, F. A. et al. 2005, Science, 307, 1938
[3] Knödelseder, J. 2009, these proceedings
[4] Sakai, S. & Madore, B. F. 1999, Astrophys. J., 526, 599
[5] Yun, M. S., Ho, P. T. T. & Lo, K. Y. A. 1994, Nature, 372, 530
[6] Fenech, D. M. et al. 2008, Mon. Not. R. Astron. Soc., 391, 1384
[7] Kronberg, P. P., Biermann, P. & Schwab, F. R. 1985, Astrophys. J., 291, 693
[8] Rieke, G. H. et al. 1980, Astrophys. J., 238, 24
[9] Weiß, A. et al. 2001, Astron. Astrophys., 365, 571
[10] Blom, J. J. et al. 1999, Astrophys. J., 516, 44
[11] Nagai, T. 2005, Search for TeV Gamma-Ray Emission from Nearby Starburst Galaxies. PhD Thesis, Univ. Utah
[12] Weekes, T. et al. 2002, Astropart. Phys., 17, 221
[13] Formin, V. et al. 1994, Astropart. Phys., 2, 137
[14] Daniel, M. K. 2008, in Proc. of the 30th Int. Cosmic Ray Conf., Vol. 3 (eds Caballero, R. et al.) 1325
[15] Sanders, D. B. et al. 2003, Astron. J., 126, 1607
[16] Acciari, V. A., et al. 2009, Nature, 462, 770
[17] Willis, K. A. et al. 1999, N. Astron. Rev., 43, 633
[18] Pohl, M. 1994, Astron. Astrophys., 287, 453
[19] de Cea del Pozo, E. et al. 2009, Astrophys. J., 698, 1054
[20] Persic, M., Raphaeli, Y. & Arieli, Y. 2008, Astron. Astrophys., 486, 143
[21] Klein, U., Wielebinski, R. & Morsi, H. W. 1988, Astron. Astrophys., 190, 41
[22] Abdo, A. A. et al. 2009, Astrophys. J., submitted

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