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Evidence for TeV gamma ray emission from Cassiopeia A

G. Pühlhofer, for the HEGRA collaboration

Max-Planck-Institut für Kernphysik, Postfach 103980, D-69029 Heidelberg, Germany

Abstract. With the HEGRA stereoscopic system of imaging atmospheric Cherenkov telescopes, TeV γ-ray emission was detected from the Supernova remnant Cassiopeia A for the first time. The detection has a statistical significance of $5\,\sigma$. A flux of $(5.8 \pm 1.2_{\text{stat}} \pm 1.2_{\text{syst}}) \times 10^{-9}\text{ph}\,\text{m}^{-2}\text{s}^{-1}$ above 1 TeV is derived. The spectral distribution is consistent with a power law with a differential spectral index $-2.5 \pm 0.4_{\text{stat}} \pm 0.1_{\text{syst}}$ between 1 and 10 TeV. The signal has a Crab-like spectrum, but only 3% of its flux. With this detection, the HEGRA system has demonstrated its currently unique ability to detect TeV γ-ray emission at the "centi-Crab" scale.

The detection of TeV γ-rays indicates that Cassiopeia A is a site of CR acceleration for particles – either nucleons or electrons – with multi-TeV energies. However, the assignment of the γ-ray emission to either or both particle populations relies on modeling. We discuss some important aspects in this paper.

1 Introduction

Cassiopeia A is the remnant of the youngest known Galactic supernova, dating back to about 1680. Its thermal emission as well as the non-thermal synchrotron emission is well-studied over a broad range of energies. The images clearly reveal the shell-type nature of the remnant. Only recent high resolution X-ray maps from the Chandra satellite (Hughes et al., 2000) indicate a central object. The distance of the supernova remnant (SNR) is estimated at 3.4 kpc (Reed et al., 1995). Its progenitor star was presumably a Wolf-Rayet star (e.g. Fesen and Becker (1991) and Iyudin et al. (1997)) with an initial mass of $\approx 30\,\text{M}_\odot$. The supernova blast wave is expanding into a wind bubble and shell system from the previous wind phases of the progenitor. The circumstellar medium can be described in terms of a shell model (Borkowsky et al., 1996), consisting of a tenuous inner bubble, a dense shell of swept-up slow red supergiant wind material, and a subsequent red supergiant wind region; according to this picture, the shock is presently propagating in the outer wind region (Berezhko et al., 2001).

Supernova remnants in general are believed to be the acceleration sites for cosmic rays, up to particle energies of at least 10^{15} eV. TeV γ-ray observations are performed to map the accompanying γ-rays and hence to locate the sources. In the case of hadronic CRs, which presumably are predominantly accelerated in the sources by diffusive shock acceleration, the π^0-decay γ-ray spectrum is supposed to extend above 1 TeV with a hard power-law spectrum $\propto E^{-2}$, the cutoff energy being dependent on the age of the SNR.

Electrons are as well accelerated by the same process, although they are much less abundant in the CRs. Hard X-ray tails of several SNRs have been interpreted as synchrotron emission of non-thermally accelerated, highly energetic electrons. In the case of Cas A the X-ray spectrum has been taken as evidence for electrons with energies up to 40 TeV (Allen et al., 1997). Model calculations showed that this electron population can lead to a detectable TeV γ-ray flux level, via Bremsstrahlung and inverse Compton (IC) upscattering of ambient soft photons.

2 HEGRA observations and results

The HEGRA Stereoscopic Cherenkov Telescope System (Konopelko et al., 1999) is located on the Roque de los Muchachos on the Canary Island La Palma, at 2200 m above sea level. It consists of 5 identical telescopes (CT 2 - CT 6), which operate in coincidence for stereoscopic detection of air showers induced by primary γ-rays in the atmosphere.

Observations on Cas A were performed in the summer months of 1997, 98 and 99. Data from the first two years already revealed evidence for TeV γ-ray emission, preliminary results were presented in Pühlhofer et al. (1999). In 1999, the data set was significantly increased. In addition,

Correspondence to: G. Pühlhofer
(Gerd.Puehlhofer@mpi-hd.mpg.de)

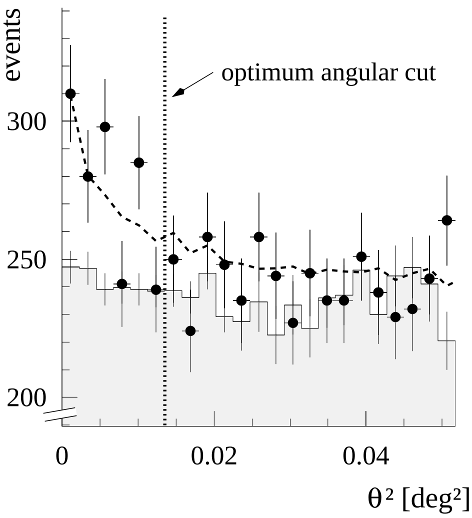

Fig. 1. Dots: Number of events vs. the squared angular distance to the position of Cas A. Shaded histogram: Background estimate; up to $\theta^2 = 0.0225\,^{\circ 2}$, data from 7 control regions is used. Therefore, the statistical error of the background estimate is much smaller than the error of the source distribution. The dashed line shows Crab excess events, measured at similar zenith angles, scaled down to 3.3%, and superimposed on a flat background. The vertical dotted line indicates the position of the optimum angular cut.

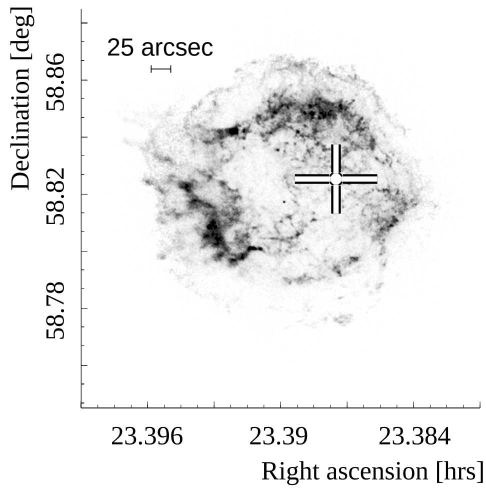

Fig. 2. Reconstructed position of Cas A in year 2000 coordinates. The error bars show the $1\,\sigma$ error on the reconstructed position. 25 arcsec is the systematic pointing uncertainty of the system. The result is superimposed to the Chandra x-ray image (courtesy of NASA/CXC/SAO).

considerable effort went into analysis techniques in order to confirm the robustness of the signal and to reduce systematic effects down to the required level. In this paper, we report on the results obtained with the total data set, which contains 232 hours of observations (Aharonian et al., 2001a).

Cas A can be observed from the HEGRA site at zenith angles of 29° or larger; the average zenith angle was 32°. Hence, the data set provides a γ-shower peak detection energy of 1 TeV for Crab-like spectra (Konopelko et al., 1999). Data were taken with 3, 4, and 5 active telescopes. Data cleaning consists of bad weather rejection and exclusion of telescopes with technical problems. Data from the telescope CT 2, which was included last into the system and was still being tuned, were excluded from this analysis.

Shower images from a telescope were accepted in the analysis if they contain at least 40 photoelectrons. The particle direction was determined using a stereoscopic reconstruction algorithm described in Hofmann et al. (1999). Events were accepted within a circle of 1° radius from the center of the field of viev (FOV). Candidates for γ-rays were selected against this background using a cut on the image shape parameter *mean scaled width* (msw) (Aharonian et al., 1999) of $0.5 < msw < 1.1$.

In Fig. 1, the number of events is plotted vs. the squared angular distance to the position of Cas A. Point-like sources are observed with the HEGRA telescope system in the so-called wobble mode, where the source is shifted relative to the center of the FOV alternatingly by $\pm 0\overset{\circ}{.}5$. In this case, the amount of the cosmic ray background which remains after the shape cut can be estimated from simultaneously gathered data. Here, seven non-overlapping, circular-shaped control regions were used, which had centers along the circle of a radius of $0\overset{\circ}{.}5$ around the center of the FOV. This setup works up to $\theta^2 = 0.0225\,^{\circ 2}$. The optimum angular cut ($\theta^2 = 0.0135\,^{\circ 2}$) was derived from Crab and Mrk 501 data. The excess significance, calculated after Li and Ma (1983), is $4.9\,\sigma$ for this straightforward evaluation.

The photon flux and energy spectrum of Cas A were derived by direct comparison to a large Crab data sample (Aharonian et al., 2000a), taken between 1997 and 2000. For the spectral analysis, we used the energy reconstruction method described in Aharonian et al. (1999), with an energy resolution of 20% per event. In order to provide equal energy thresholds and spectral acceptances for both the Cas A and the Crab reference data sets, an additional software threshold was introduced to compensate for the slightly varying detector conditions (Pühlhofer et al., 2001). The spectral distribution of Cas A was found to be comparable with the distribution measured for the Crab nebula. Under the assumption of a power law spectrum $\mathrm{d}F_\gamma/\mathrm{d}E \propto E^\alpha$ from 1 to 10 TeV, we derived a differential spectral index of $\alpha = -2.5 \pm 0.4_{\mathrm{stat}} \pm 0.1_{\mathrm{syst}}$. The flux is at a level of 3.3% of the Crab flux, this corresponds to $F_\gamma = (5.8 \pm 1.2_{\mathrm{stat}} \pm 1.2_{\mathrm{syst}}) \times 10^{-9}\,\mathrm{ph\,m^{-2}\,s^{-1}}$ above 1 TeV.

Cas A's outer shock has a diameter of 5′, which is slightly below the RMS angular resolution of the HEGRA telescope system (see studies on the Crab nebula (Hofmann and Pühlhofer, 2001; Aharonian et al., 2000b)). However, the center of the TeV emission can easily be determined from the event distribution in celestial coordinates. As Fig. 2 shows, it is well in coincidence with the position of the remnant; within statistical errors, it is consistent with the center of the

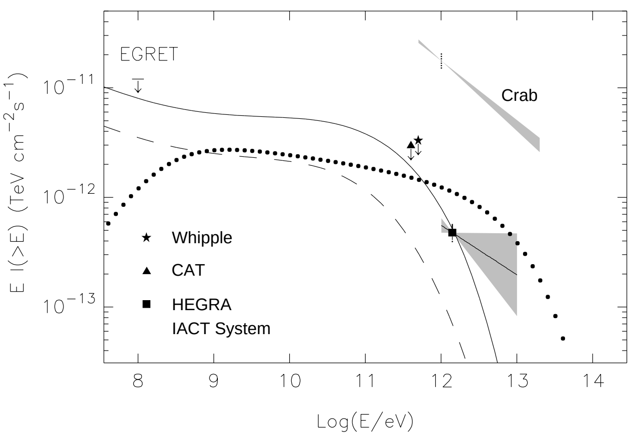

Fig. 3. The measured flux and spectral index of Cas A in the context of model predictions. The shaded area shows the 1σ error range for the measured spectral distribution under the assumption of a $E^{-\alpha}$ power law spectrum. The dotted curve represents the model spectrum for the π^0-decay flux as discussed in section 3.2; the current model however allows a renormalisation of the spectrum. The solid and dashed lines show the predicted IC plus bremsstrahlung flux for different model parameters as discussed in section 3.1. Also indicated are the upper limits measured by EGRET, Whipple and CAT.

remnant as well as with a large range of positions at the shell.

Various systematic tests were performed to confirm the γ-ray signal from Cas A (Pühlhofer, 2001). The following results were obtained: • Within statistical variations, the γ-ray signal was accumulated with a constant rate as expected for the emission from a SNR-type object. • The event numbers of the different background control regions are well consistent with the background expectation. • The γ-ray efficiency of the shape cut was estimated from the cosmic ray background rejection power; it was constant throughout the whole observing period. The background rejection power shows perfect agreement between the Cas A and the Crab reference data sets. • The fitted center of the TeV γ-ray emission was constantly centered at the object, also when separately evaluating the three years of observations. • The background-subtracted shape cut (msw) distribution shows a peak at the position and with a shape which is characteristic for γ-rays.

3 Implications for cosmic ray acceleration

The detection of TeV γ-rays proves that Cas A is a site of CR acceleration for particles – either nucleons or electrons – with multi-TeV energies. Since it is a shell-type remnant, this detection adds further support to the theory of SNRs being responsible for CR acceleration via the shock acceleration mechanism. However, further conclusions rely on the identification of the hadronic and/or leptonic nature of the high energy primary particles. Figure 3 shows the measured integral TeV flux of Cas A, together with the $1\,\sigma$ error band of the spectral index under the assumption of a power-law spectrum between 1 and 10 TeV. The TeV upper limits are taken from Lessard et al. (1999) and Goret et al. (1999). Indicated are also model spectra which are described below.

3.1 The electron transport model

A source model has been developed to predict the leptonically induced TeV emission in the framework of a multi-wavelength study (Atoyan et al., 2000a). The basic challenge is the electron transport in the highly non-homogenous source. The variations in the prediction for TeV emission via the inverse Compton (IC) mechanism, which will dominate the emission above 1 TeV, are mainly due to different deduced electron spectra; the target photon density – the synchrotron photons, the thermal dust emission in the far infrared, the optical/IR line photons, and the microwave background radiation – is well-known. X-ray emission, on the other hand, traces both the electrons and the magnetic field strength, which is typically derived to be of the order of milli-Gauss. The high energy X-ray tail and the TeV flux are spatially unresolved, and hence could be emitted in different regions with different electron spectra.

The electron transport model which attempts to take the spatial structure of Cas A into account predicts a range of possible fluxes (Atoyan et al., 2000b). The expected spectra for IC plus Bremsstrahlung emission are drawn in Fig. 3, for different model parameters (solid and dashed lines). Interestingly, the shape of the spectrum at TeV energies remains constant, and shows a steep cutoff with a differential spectral index of below -3 above 1 TeV. The chance probability that the measured spectrum can be described by this leptonic model is 15%. The agreement with the hadronic spectrum described in the next section is better, but due to the large statistical error the leptonic model cannot be ruled out.

3.2 Hadronic model spectrum

The acceleration of hadronic CR in the shock of a SNR is theoretically fairly well-understood for the case of expansion into a homogenous interstellar medium (Berezhko and Völk, 1997, 2000b; Aharonian et al., 2001b). Strong modifications are expected if the shock expands into the wind structure, e.g. of a Wolf-Rayet progenitor star (Berezhko and Völk, 2000a). These calculations show that high π^0-decay γ-ray fluxes can be expected even for young SNRs like Cas A. However, the influence of the magnetic field configuration in progenitor winds may result in largely perpendicular shocks, with strongly reduced injection efficiency, which would lower the expected γ-ray fluxes considerably (Völk, 1997, 2001).

Given these arguments, the expected absolute flux level of π^0-decay γ-rays is not well determined in the context of the general acceleration models. The value assumed in Atoyan et al. (2000b) and used here in the comparison has been chosen such that the total energy of relativistic protons is 20% of the CR energy sum of about 10^{50} ergs, which is ultimately released by an average Galactic SNR. This reasonable choice does not violate the upper limits from the EGRET detector as well as from Whipple and CAT at TeV energies. However, a renormalisation of the flux is possible in this scenario. Again, the shape of the spectrum remains as a common feature, the π^0-decay spectrum should extend up to 1 TeV with a hard $E^{-2.1..2.2}$ power-law (dotted curve in Fig. 3). The chance probability that the measured slope agrees with this model choice is 98%.

3.3 Kinetic nonlinear model of CR acceleration applied to the Cas A geometry

Recently, efforts have been made to apply the standard kinetic nonlinear theory of CR acceleration to the specific circumstellar configuration of Cas A. Details are described elsewhere in these proceedings (Berezhko et al., 2001). The model is used to calculate both the hadronic and the leptonic components of the accelerated particles, and the subsequent γ-ray emission. Straightforward application of the Cas A parameters leads to a prediction of Bremsstrahlung plus IC-emission which is close to the measured flux value, whereas the predicted hadronic emission exceeds by far the measured value. However, as discussed in the paper, there are quite some uncertainties in the choice of the parameters, and a significant suppression of the π^0-decay emission is still compatible with the theory. Whether it is possible to adjust the parameters in such a way to match all current observations is under investigation.

3.4 Synchrotron origin of the hard X-ray tail?

All current models for Cas A adopt the synchrotron interpretation of the hard tail component of the X-ray spectrum, which implies an electron population at 1 TeV and above. However, this view is not unequivocal. Recently, Laming (2001) has argued that the hard X-ray emission could also be Bremsstrahlung from nonthermal electrons with several tens of keV, energised by lower hybrid waves from shock reflected ions at quasi-perpendicular shocks.

The spatial origin of the hard X-ray component within the remnant is still unclear. For example, recent images up to 15 keV, obtained with the EPIC cameras onboard the XMM-Newton satellite, reveal a rather homogeneous distribution throughout the SNR (Bleeker et al., 2001). It is argued that this may disfavour a synchrotron origin; in simple synchrotron models, the emission should be concentrated behind the primary shock front. The models will need to be revised if the hard X-ray tail is not of synchrotron origin.

To conclude, the TeV γ-ray emission from Cas A may at present be interpreted as leptonic or hadronic emission (or a mixture of both). Studies in different wavebands as well as further theoretical modeling are needed to clarify the nature of the TeV particles detected in Cas A.

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