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Probing proton acceleration in W51C with MAGIC

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Abstract. Located in a dense complex environment, W51C provides an excellent scenario to probe accelerated protons in SNRs and their interaction with surrounding target material. Here we report the observation of extended Very High Energy (VHE) gamma-ray emission from the W51C supernova remnant (SNR) with MAGIC. The VHE observations presented here, obtained with the improved MAGIC stereo system, allow us to pinpoint the VHE gamma-ray emission in the dense shocked molecular cloud surrounding the remnant shell. MAGIC data also allow us to measure, for the first time, the VHE emission spectrum of W51C from the highest Fermi energies up to several TeV. The spatial distribution and spectral properties of the VHE emission suggest a main contribution of hadronic origin of the observed gamma-rays.

Key words. ISM: individual: W51C – cosmic rays – Gamma rays: observations

1. Introduction

Supernova Remnants (SNRs) have been suggested as one of the main locations for the acceleration of Cosmic Rays, at least for those up to the *knee* of the Cosmic Ray spectrum ($\sim 10^{15}$ eV). From a theoretical point of view Cosmic Rays could be accelerated in the expanding shock of the SNRs receiving part of the kinetical energy of the shock through the diffusive shock acceleration mechanism (Reynolds 2008). The observations of high energy (HE, $\sim$ 100 MeV to $\sim$ 100 GeV) and very high energy (VHE, from $\sim$ 100 GeV to $\sim$ 100 TeV) gamma-rays from many SNRs would be the proof that the bulk of Galactic Cosmic Rays are accelerated in SNRs, if the hadronic origin of these gamma-rays is unambiguously established. However, in most cases, electromagnetic scenarios (gamma-rays produced by up-scattering of photons through Inverse Compton scattering by accelerated electrons) and hadronic scenarios (gamma-rays produced after the decay of π^0) cannot be distinguished by looking only at the VHE gamma-ray emission. Observations at other wavelengths are needed to better understand the production mechanism of gamma-rays. In particular, the observations of gamma-rays together with observations of the synchrotron peak in radio wavelengths or X-rays are very important because they can reveal features in the spectrum that can sort out both possibilities. If leptonic channels can be discarded, cosmic ray proton acceleration can provide gamma-ray signal through two main (non exclusive) scenar-

Send offprint requests to: Ignasi Reichardt ios. In some cases, molecular cloud illumination by cosmic rays that escaped the accelerating shock is responsible for the production of VHE gamma-rays (Gabici 2009; Ohira 2011). On the other hand, a gamma-ray signal can also be provided by from clouds that are being overtaken by the SNR blast wave (Uchiyama 2010; Fang 2010).

W51C is a composite SNR with an elliptical shape and a size of $0.8^\circ \times 0.6^\circ$. It is located in the tangential point of the Sagittarius arm at a distance of 5.5 kpc (Sato 2010) and the estimated age is around 30 kyrs. The W51 complex hosts three main components: Two star-forming regions, W51A and W51B, and the SNR W51C. While W51A is separated from the other two, W51B overlaps with the North-Western rim of W51C. Shocked atomic (Koo 1997a) and molecular (Koo 1997b) gases have been observed, providing direct evidence on the interaction of the W51C shock with a large molecular cloud. W51C is also visible in X-rays showing both a shell type and center filled morphology (Koo 2002). Non-thermal X-ray emission has also been detected from the relatively bright source CXO J192318.5+140505, which is thought to be a pulsar wind nebula (PWN) associated to the SNR (Koo 2005).

H.E.S.S. discovered an extended source of gamma-rays of energies greater than 420 GeV coincident with W51C (Fiasson 2009). In their skymap, the H.E.S.S. emission is smoothed with a radius of 0.22° and it overlaps with several HII regions, the molecular gas in W51B as well as the PWN candidate CXO J192318.5+140305. The flux measured by H.E.S.S. above 1TeV is at the level of 3% of the Crab Nebula flux. Remarkably, the Milagro Collaboration reported a 3.4σ excess of gamma-rays from the same region (Abdo 2009a), which may indicate that the emission of this object extends up to the multi-TeV regime.

Fermi/LAT detected gamma-ray emission from 200 MeV to 50 GeV extended throughout W51B and W51C (Abdo 2009b). The source is found to be extended, but the relatively large PSF does not allow to tell from which of the objects of the field of view the emission comes from. The modeling of the spectral energy distribution (SED) measured by Fermi/LAT constrained by the synchrotron emission detected in radio wavelengths requires physically unrealistic parameters (e.g. electron to proton ratio $\sim$ 1). Therefore a hadronic mechanism is strongly favored as the main origin of the gamma-rays (Abdo 2009b).

2. Observations with the MAGIC telescopes

MAGIC consists of two 17 m diameter imaging atmospheric Cherenkov telescopes (IACTs) located at Roque de los Muchachos observatory, in the Canary Island of La Palma (28°46N, 17°53W), at the height of 2200 m a.s.l. Astronomical observations of VHE gamma-ray sources are performed in stereoscopic mode, were only events that trigger both telescopes are stored. This provides a major improvement of performance with respect to the single telescope observations previously done with MAGIC I (Sitarek 2011). The trigger energy threshold of the system is around 50 GeV, which allows to have ground based observations with an energy range overlapping with that of Fermi/LAT.

MAGIC observed W51C between May 17^{th} and August 19^{th} 2010. The observations were carried out in the so-called wobble mode and covered a zenith angle range between 14 and 35 degrees. As central position for the observations, the center of the Fermi/LAT source W51C (RA=19.385h, DEC=14.19°) was chosen. After applying quality cuts we collected a total of 31.1 h effective dark time. The analysis of the data was performed using the MARS analysis framework which is the standard software used for MAGIC data analysis (Moralejo 2009). The details of the analysis, as well as the general performance of MAGIC in stereoscopic mode, are reported in (Sitarek 2011).

3. Results from the MAGIC observations

MAGIC data show a spatially extended source of VHE gamma-ray events from the direction of W51C. A total of 924 excess events were found above 150 GeV in the selected dataset, which corresponds to a significance of 8σ. The significance is quantified by means of the distribution of squared angular distance, θ^2, between the source position and reconstructed events above 150 GeV after cuts. To obtain the excess, gamma-ray and background events are subtracted inside the signal region of the θ^2 distribution, which is related to the extension of the source and the point spread function (PSF) of the telescope.

The source has an extension (sigma of two-dimensional gaussian fit to the spatial distribution of the events) of $0.16 \pm 0.02°$, well above the PSF of the analysis (0.08° in the same energy range and a spectral index of -2.6). The centroid of the emission detected by MAGIC is RA=19.387 ± 0.002 h, DEC=14.18 ± 0.02°, which coincides with the centroid of the Fermi/LAT emission.

MAGIC has measured the differential energy spectrum of the VHE gamma-ray emission in the energy range of 75 GeV to 3.3 TeV. The measured differential spectrum is well fitted ($\chi^2/ndf = 4.5/5$) by a power law given by:

$$\frac{dF}{dE}=(1.25\pm0.18_{stat})\times10^{-12}\left(\frac{E}{TeV}\right)^{2.40\pm0.12_{stat}}$$

Where the expression above has units of $\mathrm{TeV^{-1}cm^{-2}s^{-1}}$. The flux at 1 TeV corresponds to 3.8% of the Crab Nebula flux, in agreement with the integral flux reported by H.E.S.S. (Fiasson 2009) above 1 TeV.

4. Discussion

MAGIC data allows a smooth connection between the Fermi/LAT and the H.E.S.S. measurements. Figure 1 shows the SED measured by the three experiments, where the H.E.S.S. measurement has been converted into a differential flux[1].

In (Abdo 2009b) three different phenomenological models are considered to explain the origin of the gamma-ray emission.

[1] The integral flux above 1 TeV reported in (Fiasson 2009) is converted into a differential flux using the MAGIC spectral index of -2.4. An error of ±0.4 is a conservative assumption in order to account for statistical and systematic uncertainties of the H.E.S.S. measurement.

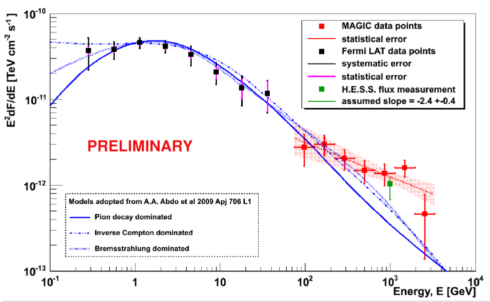

Fig. 1. SED of W51C measured by Fermi/LAT (black points), MAGIC (red points) and H.E.S.S. (green point). The red dashed line is the best fit to the MAGIC spectrum, being the shaded area the statistical uncertainty. Also shown in the figure the three different scenarios for modeling the multi-wavelength data that were used in (Abdo 2009b). Gamma-ray emission is explained by emission from a π^0 decay dominated scenario (continuous blue line), inverse Compton dominated scenario (dot-dashed line) or a Bremhstrahlung dominated scenario (dashed line).

As explained in the introduction, the scenario where gamma-ray emission is dominated by π^0 decay is favored by Fermi and radio data. However, MAGIC data points at energies above 1 TeV as well as the H.E.S.S. point (for the spectral index measured in this work) are above predictions of previous model fits to the Fermi data alone. One possibility to still conciliate the SED with the above mentioned model is that the spectrum of pre-existing cosmic rays in the cloud is different from the one assumed. The contribution of two distinct sources cannot be excluded as well.

The angular resolution of MAGIC at energies of 100 GeV is comparable to that of Fermi/LAT. At energies above 700 GeV, however, the angular resolution of the MAGIC stereo system is $\sim 0.05°$. This allows for a resolved skymap from W51C. Figure 2 shows the MAGIC view of W51C overlapped with data from different wavelengths.

The bulk of the VHE gamma-ray emission above 700 GeV follows the shape of the Fermi/LAT emission (pink line in the figure). There is also an extension of the VHE emission towards the South-East in the direction

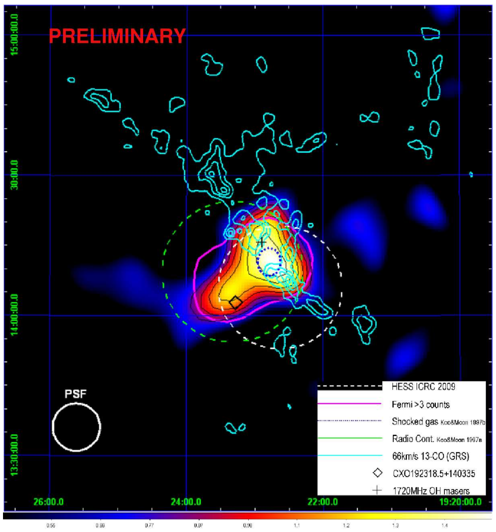

Fig. 2. The W51 region in different wavelenghts. Shown in colors the MAGIC relative flux (smoothed with a gaussian kernel of 0.065°) overlapped with the test statistics significance contours in black. The pink line shows the approximate contour of the HE emission detected by Fermi/LAT and the white dashed line shows the approximate contour of the H.E.S.S. VHE emission. The green dashed line shows the approximate contour of the SNR W51C. The dotted dark blue line shows the shocked gas region defined by (Koo 1997b). The 66 km/s ^{13}CO line emission from the Galactic Ring Survey (Jackson 2006) are shown in light blue. The PWN candidate CXO J192318.5+140335 and a 1720 MHz OH maser are also shown in the map. Details about MAGIC skymaps and test statistic are given in (Berger 2011).

of the PWN candidate. But the MAGIC emission above 700 GeV is clearly dominated by the interaction region between the supernova remnant and the dense region North-West of it (including the shocked gas region reported by Koo 1997b). The localization of the emission on top of the shocked gas is an independent indication that supports the hadronic origin as a main component for the HE-VHE gamma rays.

5. Conclusions

MAGIC observations confirm the emission of HE-VHE gamma-rays from an extended source located in the SNR W51C. The emission measured by MAGIC is spatially coincident with that reported by Fermi/LAT and H.E.S.S., and the measured SED is also in agreement with previous measurements. Moreover, MAGIC localizes the bulk of the $\sim$ 150 GeV to $\sim$ 3 TeV gamma-ray emission on the shocked gas described in (Koo 1997a,b). This fact together with the better agreement of radio data with the π^0 decay dominated model supports a hadronic scenario where propagation effects are remarkably small. Therefore W51C represents a very good case for the study of cosmic ray production mechanisms.

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