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. Detections of extended gamma-ray emission in the same region have already been reported by the Fermi and H.E.S.S. collaborations. Fermi/LAT measured the source spectrum in the energy range between 0.2 and 50 GeV, which was found to be well fit by a hadronic neutral-pion decay model. 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. The MAGIC data also allow us to measure, for the first time, the VHE emission spectrum of W51C from the highest Fermi/LAT energies up to several TeV. The spatial distribution and spectral properties of the VHE emission suggest a hadronic origin of the observed gamma rays. Therefore W51C is a prime candidate for a cosmic ray accelerator.

Keywords: Gamma-ray Astronomy, supernova remnant, cosmic rays

1 Introduction

For many years Supernova Remnants (SNRs) have been suggested as one of the main locations for the acceleration of cosmic rays, at least for those originated within the Galaxy. From a theoretical point of view, cosmic rays can be accelerated in the expanding shocks of the SNRs, receiving part of the kinetic energy of the shock through the diffusive shock acceleration mechanism [1]. The last years have provided increasing observational evidence supporting this idea. The observations of high energy (HE) and very high energy (VHE) gamma rays from many SNRs might be the proof that cosmic rays are accelerated in SNRs, if the hadronic origin of these gamma rays is unambiguously established.

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 $\pi^0$) can not 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 HE gamma rays in the range from MeVs to GeVs are very important because they can reveal features in the spectrum that can distinguish both possibilities.

Evidence of cosmic rays acceleration is provided by gamma rays emitted by molecular clouds adjacent to or shocked by SNRs [2]. VHE gamma-ray emission from W28 [3] and IC443 [4] are two examples where this effect might be responsible for the production of VHE gamma rays. In the W28 case, gamma rays might be produced by cosmic rays that escaped the accelerating SNR while in IC 443 a Crushed Cloud scenario might be at work where the molecular cloud is shocked by the blastwave region of the SNR [5].

The SNR W51C offers an excellent opportunity to study the emission of VHE gamma rays in a Crushed Cloud scenario. 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 $\sim 6$ kpc [8] 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 and molecular gases have been observed in radio data [9] [10], providing direct evidence on the interaction of the W51C shock with a large molecular cloud. X-ray emission has been detected from the star forming regions in W51A and W51B. W51C is also visible in X-rays showing both a shell type and center-filled morphology [6]. 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 [7].
Fermi/LAT detected gamma-ray emission from 200 MeV to 50 GeV extended throughout W51B and W51C [11]. The relatively large PSF does not allow to tell from which of the objects of the field of view the emission comes from. The Fermi/LAT emission region is extended in comparison to the PSF of the instrument. H.E.S.S. has also detected VHE emission above 420 GeV from an extended region coincident with the Fermi/LAT emission region [12]. In their skymap, the H.E.S.S. emission is smoothed with a radius of 0.22° [12] and, as well as in the case of Fermi/LAT, it overlaps with several HII regions, the molecular mass in W51B as well as the PWN candidate CXO-J192318.5+140305. The flux measured by H.E.S.S. above 1 TeV is at the level of 3% of the Crab Nebula flux. Finally, also the Milagro Collaboration reported a possible excess from the same source at energies above several TeV [13].

The modelling of the spectral energy distribution (SED) measured by Fermi/LAT strongly points to a hadronic mechanism as the main origin of the gamma rays. The interaction should take place in the region between the supernova remnant and the dense, complex region North-West of it. This emission might be produced by the Crushed Cloud scenario [5], where preexisting cosmic rays are accelerated after the passage of the supernova blast wave. In this case, the cloud engulfed would be those described in [9] [10].

2 Observations with the MAGIC telescopes

MAGIC consists of two 17 m diameter imaging atmospheric Cherenkov telescopes located at the Roque de los Muchachos in the Canary Island of La Palma (28°46’N, 17°53’W) at the height of 2200 m a.s.l. Astronomical observations of very high energy gamma-ray sources are performed with the two telescopes simultaneously which provides a major improvement of performance with respect to the single telescope observations previously done with MAGIC-I [15].

MAGIC observed W51C between May 17 and August 19 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=19.385 h, δ=14.19 °) was chosen. After applying quality cuts we collected a total of 31.1 h effective1 dark time. All data was taken in stereoscopic mode were only events that triggered both telescopes are stored.

The trigger energy threshold of the system is around 50 GeV [15]. This is the lowest energy threshold among IACTs in operation and provides the chance to have ground based observations with an energy range overlapping with that of Fermi/LAT. The analysis of the data was performed using the MARS analysis framework which is the standard software used for MAGIC data analysis [16]. The details of the analysis, as well as the general performance of MAGIC in stereoscopic mode, are reported in [15] [14].

3 Results from MAGIC observations

MAGIC data show a spatially extended excess of VHE gamma-ray events from the direction of W51C. A total of 924 excess events were found above 150 GeV in the analyzed 31.1 hours of effective time (see figure 1). This excess corresponds to a significance of 8.29 σ. The source has an extension (sigma of two-dimensional gaussian fit) of 0.16±0.02°, well above that of the point spread function (PSF) of the analysis (0.08° in the same energy range from a spectral index of -2.6). The centroid of the emission detected by MAGIC is coincident with the centroid of the Fermi/LAT emission: RA=19.387±0.002 h, δ=14.18±0.02°. A skymap of the MAGIC observation at energies above 150 GeV is shown in figure 2. Details about MAGIC skymaps and test statistic are given in [17].

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 by a power law as can be seen in figure 3 ($\chi^2_{ndf} = 4.5/5$). The obtained spectral index of the VHE gamma-ray emission is $-2.40 ± 0.12_{stat}$. The flux at 1 TeV corresponds to 3.8% of the Crab Nebula in agreement with the integral flux reported by H.E.S.S. [12] above 1 TeV. The obtained flux in units of TeV$^{-1}$ cm$^{-2}$ s$^{-1}$ is given by:

$$\frac{dF}{dE} = (1.25 \pm 0.1_{stat}) \times 10^{-12} \left(\frac{E}{\text{TeV}}\right)^{(-2.40 \pm 0.12_{stat})}$$

1. Due to deadtime of the MAGIC-II telescope readout system the effective observation time is always lower than the real observation time.

Figure 1: Distribution of the squared angular distance between the reconstructed VHE gamma-ray events (red points) and background (black points) above 150 GeV after cuts, and the source position. The vertical dotted line marks the region defined to compute the excess events.

Figure 2: A skymap of the MAGIC observation at energies above 150 GeV is shown with the vertical dotted line marks the region defined to compute the excess events.
Figure 2: VHE gamma-ray emission from W51C obtained with the MAGIC telescopes above 150 GeV. The map has been smoothed with a gaussian kernel of $\sigma=0.10^\circ$. The color scale shows the relative flux of gamma rays (excess events normalized to the number of background events) and the black contours are different levels of the test statistic variable (Li & Ma eq. 17 [18] applied on a smoothed and modelled background estimation. It roughly corresponds to a gaussian significance. More details given in [17]). In the figure the region defined for integrating the signal (dotted line) and the PSF after smearing (bottom left inset) are also shown.

Figure 3: Measured flux from W51C with the MAGIC telescopes. The red points show the differential fluxes. The red line represents the best fitted power-law. As a reference the measured by MAGIC-I differential energy spectrum from the Crab Nebula is also shown.

4 Discussion

The MAGIC data fill the gap between the Fermi/LAT and the H.E.S.S. measurements. Figure 4 shows the SED measured by Fermi/LAT and MAGIC together with the H.E.S.S. measurement converted into a differential flux. MAGIC data agrees well with the Fermi/LAT and H.E.S.S. measurements. In the same figure the predictions from the phenomenological model used by Fermi/LAT in [11] to explain the origin of the gamma-ray emission are also shown. Three different scenarios are considered: one where gamma-ray emission is dominated by $\pi^0$ decay and two more where the gamma-ray emission is mainly dominated by inverse Compton or Bremsstrahlung.

VHE MAGIC data points as well as H.E.S.S. point seem to be slightly above predictions from the model in all scenarios at energies above 1 TeV. Although this seems to favour the electromagnetic scenarios, it may also be due to the spectra of pre-existing cosmic rays in the cloud being different from the one assumed in the model (the galactic cosmic ray spectrum). In addition, electromagnetic scenarios have problems to fit the radio data and they need a ratio of radiating electrons to protons in the SNR shock very far from what it is observed in cosmic rays. Taken into account all this, the hadronic scenario is the most likely one to explain the origin of the HE-VHE emission.

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 $\simeq 0.05^\circ$. This allows for a higher-resolved skymap from W51C. Figure 5 shows the MAGIC view of W51C overlapped with data from different wavelengths. The bulk of the VHE gamma-ray emission above 700 GeV is coincident with the shocked gas region reported by Koo et al. in [10]. There is also an extension of the VHE emission towards the South-East in the direction of the PWN candidate, following the shape of the Fermi/LAT HE emission. This may be an indication for an additional, harder emission component from the PWN, that might explain al-

2. The integral flux above 1 TeV reported in [12] is converted into a differential flux using the MAGIC spectral index of -2.4. An error of $\pm 0.4$ is assumed in order to obtain the error bars shown.
so the differences with respect to the models at VHE in the SED. MAGIC emission above 700 GeV is contained within the region defined by Fermi/LAT (pink line in the figure), but clearly favours the origin of the gamma-ray emission to be located in the shocked gas region rather than the PWN candidate. This also supports the hadronic origin of the HE-VHE gamma rays.

5 Conclusions

MAGIC observations confirm the emission of HE-VHE gamma rays from a extended source located in the SNR W51C. The emission measured by MAGIC is spatially coincident with that reported by Fermi/LAT, and the measured SED is in agreement with the Fermi/LAT and H.E.S.S. measurements. Moreover, the higher angular resolution provided by MAGIC shows that the bulk of the VHE gamma-ray emission comes from the shocked molecular cloud located where the SNR shock engulfs a large molecular cloud, creating a shocked gas region distinguishable in the radio data. This fact, and the better agreement of radio data with the hadronic scenario, suggests that the gamma-ray emission has most likely a hadronic origin as it is expected in the case of gamma rays produced in a crushed cloud scenario.

References


Figure 5: Map of W51C region in different wave lenses. Shown in colors the MAGIC relative flux (smooth by 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 et al. [10]. On the left map the molecular clouds measured with the 66 km/s 13-CO line are shown in light blue. On the right map, the green contours show the radio data from Koo & Moon [9] in green. The X-ray source and PWN candidate CXO192318.5+140335 and a 1720MHz OH maser are also shown in the map.