

Hadron acceleration imprints in the supernova remnant W51C observed with the MAGIC telescopes

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Abstract: The middle-aged supernova remnant (SNR) W51C interacts with the molecular clouds of the star-forming region W51B, making the W51 complex an ideal target to study cosmic ray acceleration. Gamma-ray emission from this region was discovered by Fermi/LAT and H.E.S.S., but in both cases it was not clear whether it originated from the SNR shell, the molecular cloud or a pulsar wind nebula (PWN) candidate. Furthermore, based on ionization measurements in the mm regime, indications have been reported of an enhanced low-energy proton flux in the interaction region between the SNR and MC. By conducting a deep observation, MAGIC detected an extended emission from W51 at > 11 sigma significance level. The MAGIC data span the energy range extending the highest Fermi/LAT energies (~ 50 GeV) up to ~ 5 TeV. The MAGIC spectrum can be described as a single power law with an index $2.58 \pm 0.07_{\text{stat}} \pm 0.22_{\text{syst}}$. A morphological study in two different photon energy ranges suggests that $\sim 80\%$ of the emission comes from the interaction between the SNR and the molecular clouds, and $\sim 20\%$ comes from a tail that extends towards the PWN candidate CXO J192318.5+140305. The broad-band spectral energy distribution can be explained with a hadronic model involving ~ 50 TeV protons, but not with (simple) leptonic models. This result, together with the morphology of the source, suggests that we observe the signature of ongoing ion acceleration that takes place in the interaction region between the SNR and the clouds. Such a scenario requires a $\sim 16\%$ efficiency conversion of the SNR kinetic energy into cosmic rays and it adds strong evidence that cosmic rays below the knee are accelerated in SNRs.

Keywords: acceleration of particles, gamma rays, supernova remnants, molecular clouds, cosmic rays

1 Introduction

The here presented results summarize the results published in [1]. Located at the tangential point ($l = 49^\circ$) of the Sagittarius arm of the Galaxy, the W51 region lies at a distance of ~ 5.5 kpc [2]. The three main components consisting of the star forming regions W51A and W51B and the supernova remnant W51C are identified according to radio continuum observations. The age of W51C is estimated to be 30 kyrs [3]. Several observations [4, 5, 6] provide evidence that the shock wave of W51C collides with the giant molecular cloud complex W51B and thus direct interaction between them. Moreover, recent measurements [7] showed over-ionization of the gas in W51B in certain locations close to W51C coinciding with the shocked gas. They conclude this excess in ionization implies the existence of an intense flow of freshly accelerated cosmic rays (CRs) that, through proton-proton collisions, ionize the hydrogen in the adjacent cloud. Furthermore, a hard X-ray source CXO J192318.5+140305 is detected, representing possibly a pulsar wind nebula [8, 9] (PWN) associated with the SNR. An extended source of gamma rays was first detected by the H.E.S.S. telescopes reporting an integral flux above 1 TeV of about 3% that of the Crab Nebula [10]. However, the presented morphological and spectral information was not enough to attribute the origin of the emission to any particular object in the field of view. Also, the Large Area Telescope (LAT) on board the *Fermi* satellite detected an extended source between 200 MeV and 50 GeV coincident with the H.E.S.S. source [11], favoring an hadron-

ic origin of the observed emission. Moreover, MILAGRO reports a 3.4σ excess with median energy of 10 TeV coincident with the *Fermi*/LAT source [12]. MAGIC observed the source to determine the spatial origin of the emission, the spectral behavior in the very high energy regime and thus constraining the possible acceleration of cosmic rays in the system.

2 MAGIC data, results and their interpretation

MAGIC observed W51 in 2010 and 2011 resulting in a total amount of 53 h effective dark time. An extended source has been detected with more than 11 standard deviations above an energy threshold of 150 GeV. The centroid of the emission is spatially coincident with the region where the shock of the SNR interacts with the molecular complex W51B. We obtain the intrinsic source extension defined as the σ of a two dimensional Gauss function as $0.12 \pm 0.02_{\text{stat}} \pm 0.02_{\text{syst}}$ degrees. The obtained spectrum ranges from 75 GeV up to 5.5 TeV and follows a power law with a spectral index of $\Gamma = 2.58 \pm 0.07_{\text{stat}} \pm 0.22_{\text{syst}}$, and a normalization constant at 1 TeV of $N_0 = (9.7 \pm 1.0_{\text{stat}}) \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$. The spectral slope is in agreement with the one obtained by [11] above ~ 10 GeV and the flux above 1 TeV is in agreement with the value obtained by [10]. Furthermore we performed morphological studies in two energy ranges: 300–1000 GeV and above 1000 GeV.

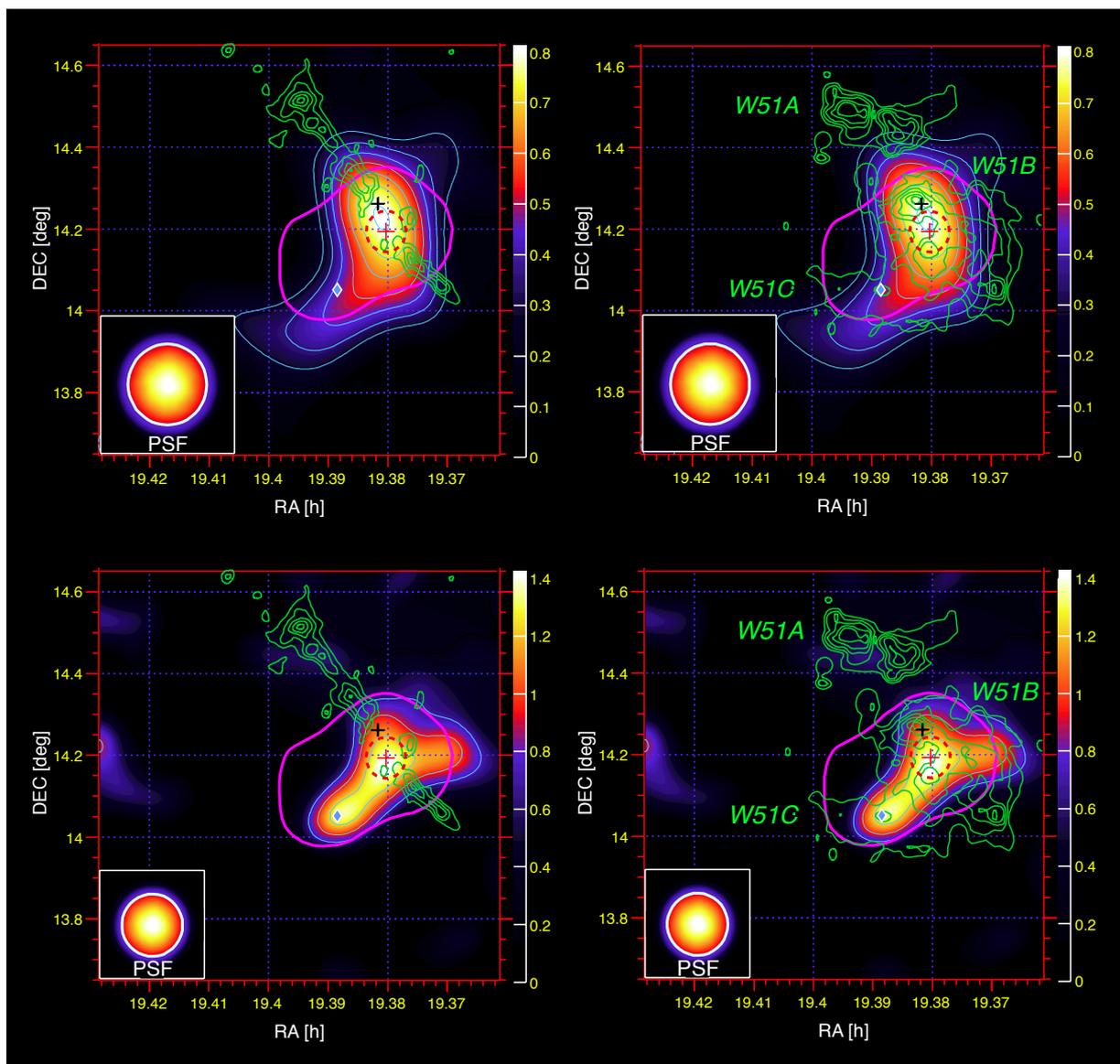


Fig. 1: Relative flux maps: From 300 GeV to 1000 GeV (top) and > 1000 GeV (bottom). On the left hand side the MAGIC data are combined with the ^{13}CO ($J=1-0$) intensity maps from the Galactic Ring Survey (see http://www.bu.edu/galacticring/new_index.html) integrated between 63 and 72 km s^{-1} shown as thin contours. On the right hand side the thin contours represent the 21 cm radio continuum emission from [5]. In all maps the diamond represents the position of CXO J192318.5+140305 and the cross the position of the OH maser emission [9, 4]. The dashed ellipse (with a cross in the center) represents the region of shocked atomic and molecular gas [6, 5]. The 3 counts contour above 1 GeV determined by *Fermi*/LAT is displayed by the single thick contour. In each picture the gaussian sigma of a point-like source (PSF) after the applied smearing is shown. The grey scale represents the relative flux as measured with MAGIC. In addition the test statistics contours of MAGIC are shown starting at 3 and increasing by one per contour. Credit: J. Aleksic et al. A&A, 541, A13, 2012

Figure 1 shows the obtained skymaps from MAGIC in the context of multi wavelength data. The main aspects in both energy ranges are as follows: the centroid of the emission always coincides with interaction region between remnant and cloud. No significant gamma ray emission is observed from the outer parts of W51B, challenging the interpretation that escaped CRs produce the observed emission by illuminating W51B from the outside. Instead the interpretation that the emission arises from CRs being accelerated in the interaction region explains the observed morphology and is supported by the enhanced CR ioniza-

tion measured in this region [7]. In both energy ranges we see a feature of the emission extending towards the position of the possible PWN. From the available data it is not clear if the PWN is an independent source in very high energies. However we determine that its contribution to the overall observed flux by MAGIC would be only $\sim 20\%$ not showing any significant dependence on energy. Thus we interpret all emission to have a common origin.

We model the observed multi wavelength radiation assuming a broken power law spectrum of highly relativistic protons and electrons. No simple one-zone leptonic s-

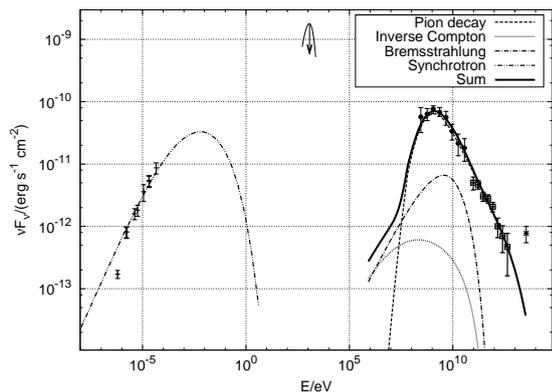


Fig. 2: Model of the multi-wavelength SED in the hadronic-dominated scenario. The dashes with error bars are 21cm radio continuum, circles represent *Fermi*/LAT data, squares are the data obtained by MAGIC and the star represent the MILAGRO data point. The upper limit in the X-ray regime is obtained from *ROSAT* data. Credit: J. Aleksic et al. *A&A*, 541, A13, 2012

scenario (Bremsstrahlung or Inverse Compton) can explain both the radio and the gamma ray emission, in agreement with results obtained previously by [11]. We find that the multi-wavelength data can be well described in a hadronic scenario where $\sim 16\%$ of the kinetic energy of the remnant has been transferred into cosmic rays (see Fig. 2). The model assumes an ambient density of $10 \text{ particles cm}^{-3}$, a magnetic field strength of $53 \mu\text{G}$, and an electron to proton ratio of 0.0125. The electron and proton spectra are described by a broken power law of slope -1.5 before the break at 10 GeV and a slope of -2.7 afterwards, which is compatible to similar objects [13, 14]. The measurement by MILAGRO is not explained in this scenario and would require an additional component at higher energies.

Recently, [22] reported no evidence for interaction between the remnant W51C and the high speed HI discovered by [5] based on data from the 21 cm continuum and HI-line data from the VLA Galactic Plane Survey. The authors obtain a distance to W51C of 4.3 Kpc placing the remnant 1 kpc ahead of the region W51B. Based on this results the authors raise doubt on the hadronic interpretation of the gamma-ray emission. We stress that no single zone leptonic dominated model, independent of the assumed density, can explain the non-thermal emission discussed here (see also [20]) which is agreement with previous findings [11]. Also [21] investigated the W51 region with new radio observations from the VLA, VLBA, MERLIN, JCMT, and CSO along with archival data from Spitzer, ROSAT, ASCA, and Chandra. These authors report new evidence for interaction between the remnant W51C and the region W51B, in agreement with earlier results. Moreover, they conclude that the absence of 400 cm synchrotron emission towards the southern part of W51B, places W51C behind W51B for this line of sight as the emission here is suppressed by free-free absorption in the dense environment of W51B.

3 Conclusions

MAGIC extends the gamma ray spectrum of the supernova remnant W51C almost without gap from the *Fermi*/LAT energies to $\sim 5 \text{ TeV}$. The centroid of the emission is pin pointed to the interaction region of the supernova shock wave (W51C) and the molecular cloud (W51B). From the here determined morphology and the available multi-wavelength data it is suggested that we observe ongoing ion acceleration at least up to 50 TeV in a medium age supernova remnant interacting with a molecular cloud. Recently, [15, 16] measured the low energy cut off predicted for hadronic gamma-ray sources in the remnants W44 and IC443, identifying them clearly as hadron accelerators. While the here presented results on W51C clearly favor a hadronic scenario, a measurement of the pion cut off would add final proof. While it is now clear that (at least some) SNRs do accelerate protons to relativistic energies, the observed spectral shapes are significantly steeper than E^{-2} , predicted by diffusive shock acceleration (see e.g. [17]). As of today the reasons for this discrepancy is not understood. Possible suggested explanations involve the escape of particles from their accelerator [19], or modifications in the theory of shock acceleration [18]. Despite the evidence that (at least some) SNRs are sources of CRs with energies below the knee ($\sim 3 \times 10^{15}$), the underlying physical processes are not yet fully understood. Future observations at high and very high energies will improve the current data, enlarge the number of known hadronic gamma ray emitters, and thus add important information to reveal the origin of galactic cosmic rays.

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References

- [1] J. Aleksic, et al. (MAGIC coll.), *A&A* 541, A13 (2012).
- [2] M. Sato, M. J. Reid, A. Brunthaler, and K. M. Menten, *ApJ* 720, 10551065 (2010).
- [3] B.-C. Koo, K.-T. Kim, and F. D. Seward, *ApJ* 447, 211 (1995).
- [4] A. J. Green, D. A. Frail, W. M. Goss, and R. Otrupcek, *AJ* 114, 2058 (1997).
- [5] B.-C. Koo, and D.-S. Moon, *ApJ* 475, 194 (1997).
- [6] B.-C. Koo, and D.-S. Moon, *ApJ* 485, 263 (1997).
- [7] C. Ceccarelli, P. Hily-Blant, T. Montmerle, G. Dubus, Y. Gallant, and A. Fiascon, *ApJ* 740, L4+(2011).
- [8] B.-C. Koo, J.-J. Lee, and F. D. Seward, *AJ* 123, 16291638 (2002).
- [9] B.-C. Koo, J.-J. Lee, F. D. Seward, and D.-S. Moon, *ApJ* 633, 946952 (2005).
- [10] A. Fiascon, V. Marandon, R. C. G. Chaves, and O. Tibolla (H.E.S.S. Coll.), in Proceedings of the 31st ICRC, Lodz, 2009.
- [11] A. A. Abdo et al. (Fermi Coll.), *ApJ* 706, L1L6 (2009).
- [12] A. A. Abdo et al. (MILAGRO Coll.), *ApJ* 700, L127L131 (2009).
- [13] A. A. Abdo et al. (Fermi Coll.), *ApJ* 712, 459468 (2010).
- [14] A. A. Abdo et al. (Fermi Coll.), *ApJ* 718, 348356 (2010).

- [15] Ackermann, M., Ajello, M., Allafort, A., et al. (2013), *Science*, 339, 807
- [16] Guiliani, A., Cardillo, M., Tavani, M., et al. (2011), *ApJ*, 742, L30
- [17] Caprioli, D., Kang, H., Vladimirov, A. E., & Jones, T. W. (2010), *MNRAS*, 407, 1773
- [18] Caprioli, D., *Journal of Cosmology and Astroparticle Physics*, 7, 38, (2012)
- [19] Malkov, M. A., Diamond, P. H., Sagdeev, R. Z., Aharonian, F. A., & Moskalenko, I. V. 2013, *ApJ*, 768, 73, 13 pp. (2013)
- [20] Krause, Julian D. G. (2013): Resolved gamma ray emission of the supernova remnant W51C and HESS J1857+026 obtained with the MAGIC telescopes. Dissertation, LMU Munich: Faculty of Physics
- [21] Brogan, C. L. et al., ArXiv e-prints, 1305.2793, (2013)
- [22] Tian, W. W. and Leahy, D. A., ArXiv e-prints, 1305.0325 (2013)