Efficient particle acceleration from HESS J1640-465 and the PeVatron candidate HESS J1641-463

A. Mares[1], M.-H. Grondin[1,2], M. Lemoine-Goumard[1,2]
On behalf of the *Fermi*-LAT collaboration

1. CENBG – CNRS/IN2P3, Bordeaux, France
2. Funded by contract ANR-17-CE31-0014

There are only a few PeVatron candidates known in our Galaxy which might contribute particles up to the knee of the cosmic-ray spectrum. HESS J1641-463, a gamma-ray source located in the Galactic plane and detected by H.E.S.S. above 4 TeV, is one of them. Characterized as a point source with a hard spectral index, HESS J1641-463 remains unidentified but is coincident with a radio SNR G338.5+0.1 and the dense HII region G338.4+0.0. With an angular extent of only 0.07º, the high energy gamma-ray source HESS J1640-465, coincident with the composite SNR G338.3-0.0 and the pulsar PSR J1640-4631, was originally classified as an extremely powerful SNR. In this context, the escape of cosmic-ray protons accelerated by G338.3-0.0 colliding with the ambient dense gas would be able to produce the emission of HESS J1641-463, providing a self-consistent explanation for the gamma-ray emission of both sources.

Using 100 months of *Fermi*-LAT pass 8 data, we analyzed these two sources from 200 MeV to 1 TeV. Our extensive morphological and spectral analyses provide new constraints on the origin of the gamma-ray emission as well as the efficiency of these two H.E.S.S. sources to accelerate protons and contribute to the Galactic cosmic-ray flux around the knee.

HESS J1640-465 & HESS J1641-463

HESS J1640-465:

- Extended gamma-ray source as seen with H.E.S.S. ($\sigma = 0.072° \pm 0.003°$) [1]
- Coincident with the radio SNR G338.3-0.0 [2]
- X-ray pulsar PSR J1640-4631 and PWN located at the center of the SNR [3]:
  - $\tau_c = 3350$ years, $4.4\mathrm{x}10^{36}$ erg.s^{-1}
- First detection by *Fermi* reported a soft spectrum [4]
- Second analysis detected HESS J1641-463 and reported a harder spectrum [5]
- Latest analysis reports a harder spectrum consistent with a PWN emission [6]

=> Whatever the origin, very luminous gamma-ray source

HESS J1641-463:

- Point source detected with H.E.S.S. and *Fermi* 0.25º away from HESS J1640-465
- Coincident with radio SNR G338.5+0.1 and dense HII region G338.4+0.0 => distance estimate of 11 kpc [7]
- Very hard spectrum at TeV energy (H.E.S.S., $\Gamma \sim 2.1$) [8]

=> excellent PeVatron candidate

Fermi data analysis

- 100 months of *Fermi*-LAT Pass 8 data
- Zenith Angle < 90º, SAA excluded
- IRFs: P8R3_SOURCE_V2, Science Tools: v11-07-00
- Region of interest of 15º x 15º
- Model including 4FGL sources up to 20º [9]
- Spectral parameters free for bright sources (TS>100) and within a radius of 4°
- Templates of diffuse emission:
  gll_iem_v07.fits
  iso_P8R3_SOURCE_V2_v1.txt
- Maximum likelihood binned analysis combines the four PSF event types in a joint likelihood function
- Using the Fermipy package [10] between 1 GeV and 1 TeV, we search for new sources in the ROI, localize and test the extension of HESS J1640-465 and HESS J1641-463
- Best spatial model used to derive the spectrum between 200 MeV and 1 TeV

Morphology

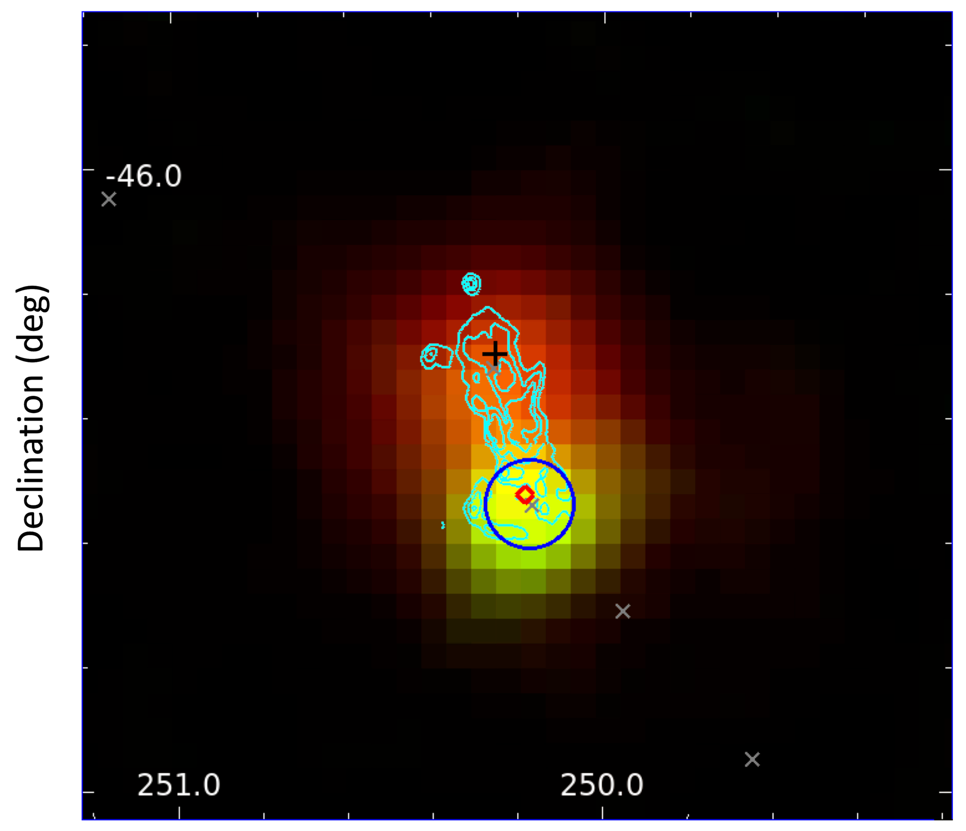

Figure 1 : Superimposed *Fermi*-LAT TS map above 1 GeV (red) and above 10 GeV (green) of a 1.5º x 1.5º region around HESS J1640-465. Sources from the 4FGL catalog [9] are indicated with grey crosses. Our best position of the H.E.S.S. point source HESS J1641−463 is marked with a black plus while the best position and extension of the H.E.S.S. Gaussian HESS J1640−465 is represented by a blue circle. The red diamond indicates the position of the pulsar PSR J1640−4631. Radio continuum at 843 MHz is shown as cyan contours [2]. All sources are included in the background model except HESS J1640-465 and HESS J1641-463.

- 9 sources added in the model with TS > 25
- **HESS J1640-465:**
  - $\sigma = 0.064° \pm 0.013°$ with a 2D-Gaussian,
  - $TS_{ext} = 40$
  - no significant improvement with respect to H.E.S.S. template

  => Use the H.E.S.S. template
- **HESS J1641-463:**
  - not significantly extended.
  - Best localization: $(250.25° \pm 0.01°_{stat}; -46.30° \pm 0.01°_{stat})$

Spectral energy distributions

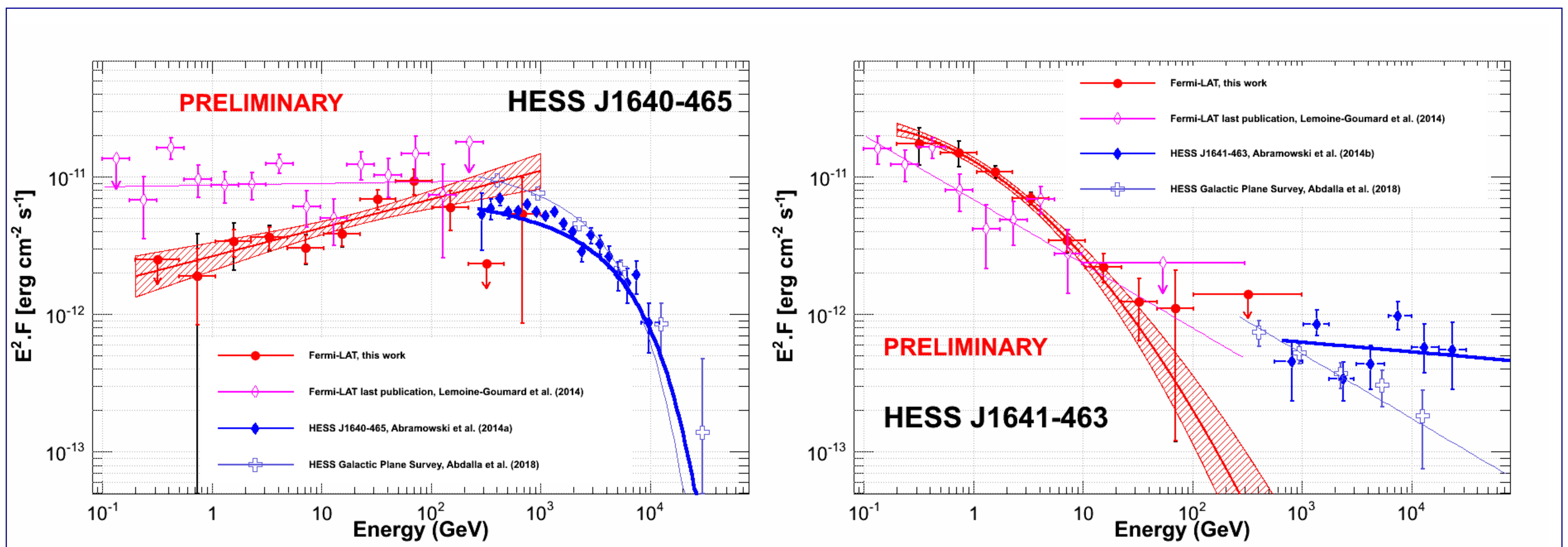

Figure 2 : Spectral energy distributions of HESS J1640-465 (Left) and HESS J1641-463 (Right). The red line and butterfly show the best fit derived above 200 MeV for both sources. For each of the 11 energy bins spaced uniformly in log space between 200 MeV and 1 TeV, the statistical errors are shown in red, while the black lines take into account both the statistical and systematic errors. A 95% C.L. upper limit is computed when the statistical significance is lower than 2σ.

- **HESS J1640-465:**
  - no significant curvature => simple power-law: $K.\left(\frac{E}{E_0}\right)^{-\Gamma}$
  - $K = (7.7 \pm 0.8_{stat} \pm 0.6_{syst})\mathrm{x}10^{-15}$ MeV^{-1}.cm^{-2}.s^{-1} ; $\Gamma = 1.8 \pm 0.1_{stat} \pm 0.2_{syst}$, $E_0 = 20$ GeV
- **HESS J1641-463:**
  - 4σ improvement using a log-parabola ($K.E^{-(\alpha+\beta.\log(E/Eb))}$)
  - $K = (4.9 \pm 0.1_{stat} \pm 0.3_{syst})\ \mathrm{x}10^{-13}$ MeV^{-1}.cm^{-2}.s^{-1}
  - $\alpha = 2.7 \pm 0.1_{stat} \pm 0.2_{syst}$; $\beta = 0.1 \pm 0.03_{stat} \pm 0.1_{syst}$; $E_b = 3$ GeV
- **Systematics taken into account:**
  - uncertainties in our model of the Galactic diffuse emission,
  - uncertainties on the morphology of HESS J1640-465
  - uncertainties in our knowledge of the *Fermi*-LAT IRFs

Conclusions

Thanks to a larger dataset and to an improved event reconstruction, *Fermi*-LAT analysis of the region containing HESS J1640–465 and HESS J1641–463 provide new clues on the origin and acceleration mechanisms of these two TeV sources. For the case of HESS J1640–465, the harder spectrum revealed in this new analysis connects perfectly with the TeV spectral points. It is not clear yet if we are seeing the SNR or the PWN. But, whatever the origin of the source, the gamma-ray spectral shape revealed here is very similar to leptonic dominated scenario in which electrons are radiating through inverse Compton scattering. In the case of HESS J1641–463, the connection between the steep spectrum detected by this new analysis and the H.E.S.S. spectrum remains unclear and points toward two different mechanisms or sources producing the gamma-ray photons detected in each energy band. The curvature detected for the first time with the *Fermi*-LAT data could indicate a pulsar origin at low energy and a PWN origin in the TeV domain, as for the case of HESS J1356–645.

These two intriguing luminous and efficient sources could be two PSR/PWN systems, highlighting again the dominant role of pulsars and their nebulae at gamma-ray energies.

Acknowledgments

The Fermi LAT Collaboration acknowledges generous ongoing support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as scientific data analysis. These include the National Aeronautics and Space Administration and the Department of Energy in the United States, the Commissariat à l'Energie Atomique and the Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules in France, the Agenzia Spaziale Italiana, the Istituto Nazionale di Fisica Nucleare, and the Istituto Nazionale di Astrofisica in Italy, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), High Energy Accelerator Research Organization (KEK) and Japan Aerospace Exploration Agency (JAXA) in Japan, and the K. A. Wallenberg Foundation and the Swedish National Space Board in Sweden. Additional support for science analysis during the operations phase from the following agencies is also gratefully acknowledged: the Instituto Nazionale di Astrofisica in Italy and the Centre National d'Etudes Spatiales in France.

SUPERNOVA REMNANTS II
AN ODYSSEY IN SPACE AFTER STELLAR DEATH

[1] Abramowski A., Aharonian F., et al., 2014, MNRAS, 439, 2828
[2] Whiteoak J. B. Z. & Green A. J., 1996, A&AS, 118, 329
[3] Gotthelf E. V., Tomsick J. A., Halpern J. P., et al., 2014, ApJ, 788, 155
[4] Slane P., Castro D., Funk S., et al., 2010, ApJ, 720, 266
[5] Lemoine-Goumard M., Grondin M.-H., et al., 2014, ApJ, 794, L16
[6] Xin Y.-L., Liao, N.-H, Guo, X.-L., et al., ApJ, 867, 55
[7] Kothes, R. & Dougherty, S. M. 2007, A&A, 468, 993
[8] Abramowski A., Aharonian F., et al., 2014, ApJ, 794, L1
[9] The Fermi-LAT collaboration, 2019, arXiv:1902.10045
[10] Wood M., Caputo R., 2017, proceedings of the 35th ICRC