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Young massive stellar clusters as cosmic-ray sources: the case of Westerlund 1

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Young massive stellar clusters are increasingly discussed as major contributors to the flux of Galactic cosmic rays. Westerlund 1, being the most massive young stellar cluster in the Milky Way, is a prime target to study in this regard. We present results from deep observations of the region around Westerlund 1 in very-high-energy gamma rays with the H.E.S.S. array of Cherenkov telescopes. We observe a large-scale (~2° diameter) emission region with a shell-like structure, extending far beyond the stellar cluster itself. No indications for a variation of the source morphology with energy could be found, the combined energy spectrum extends to several tens of TeV. Apart from Westerlund 1, no other potential counterparts were found that can be responsible for the bulk of the gamma-ray emission. We discuss various different explanations for the origin of the gamma-ray emission, considering both cosmic-ray acceleration at shock fronts within the cluster as well as scenarios related to the powerful combined cluster wind.

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1. Introduction

Young massive stellar clusters have been proposed as cosmic-ray acceleration sites already almost 40 years ago [1]. Recently, there has been an increased interest in young massive stellar clusters as potential sources of the highest-energy cosmic rays [2], and several recent works have studied cosmic-ray acceleration at various sites connected to young massive stellar clusters and their surrounding superbubbles (e.g. [3,4]). With an estimated mass of around $10^5\,M_\odot$ [5], Westerlund 1 is the most massive young stellar cluster in the Milky Way, and thus a target of prime interest to test these predictions. It is located about 4 kpc away from Earth [6] and 3 – 5 Myr old [5]. Its half-mass radius is approximately 1 pc [7]. In 2012, the H.E.S.S. Collaboration has reported the detection of an extended γ-ray source – denoted HESS J1646−458 – around Westerlund 1 [8]. Due to the limited data set available at the time, no definitive conclusions on the association of the γ-ray emission could be drawn. Here, we summarise results from a recently published, updated study of the γ-ray emission surrounding Westerlund 1 with the H.E.S.S. telescopes [9]. All results and figures presented in this proceedings article are based on this study, to which the reader is referred for further details.

2. H.E.S.S. data set and analysis

H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes, located in the Khomas highland in Namibia [10,11]. The data set for HESS J1646−458 comprises 362 observations runs, corresponding to a total observation time of 164.2 h. Only data from the four smaller (12 m diameter) H.E.S.S. telescopes have been considered in this study. The analysis has been carried out above an energy threshold of 0.37 TeV. γ ray-like events have been selected using a multivariate analysis technique [12] and reconstructed with the `ImPACT` algorithm [13]. For the high-level analysis, we employed the `Gammapy` package (v0.17) [14,15] to carry out a three-dimensional likelihood analysis. To model the residual background of cosmic ray-induced air shower events, we utilised the approach outlined in [16].

3. Results

In Fig. 1(a), we show a γ-ray flux map of the region around Westerlund 1. The γ-ray emission of HESS J1646−458 is largely extended, about 2°, or 140 pc in diameter. Remarkably, it is not peaked at the position of the stellar cluster. Instead, a shell-like structure that is almost centred on the cluster can be made out, with several bright peaks in addition. A detailed investigation of possible counterparts for the emission has revealed that while the two energetic pulsars PSR J1648−4611 and PSR J1650−4601 may contribute locally in their immediate surroundings, only cosmic rays accelerated by Westerlund 1 can be made responsible for the majority of the emission.

The shell-like morphology of the emission is also reflected in the radial excess profile shown in Fig. 1(b) (black line). The peak at ~0.5° corresponds to a distance from the centre of ~34 pc. To test for a possible energy-dependent morphology, we also computed radial profiles in different energy bands (coloured lines). The profiles are all compatible with each other, implying that we find no indications for an energy-dependent morphology of the emission.

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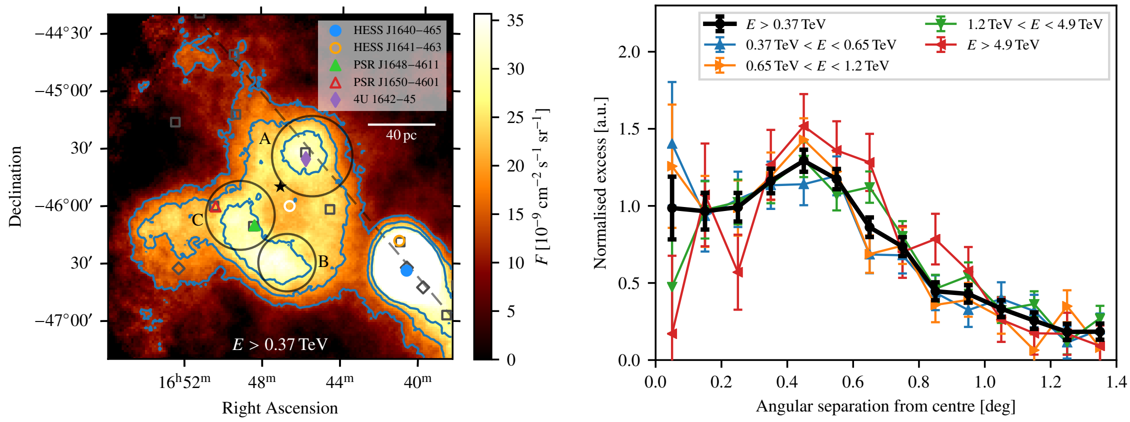
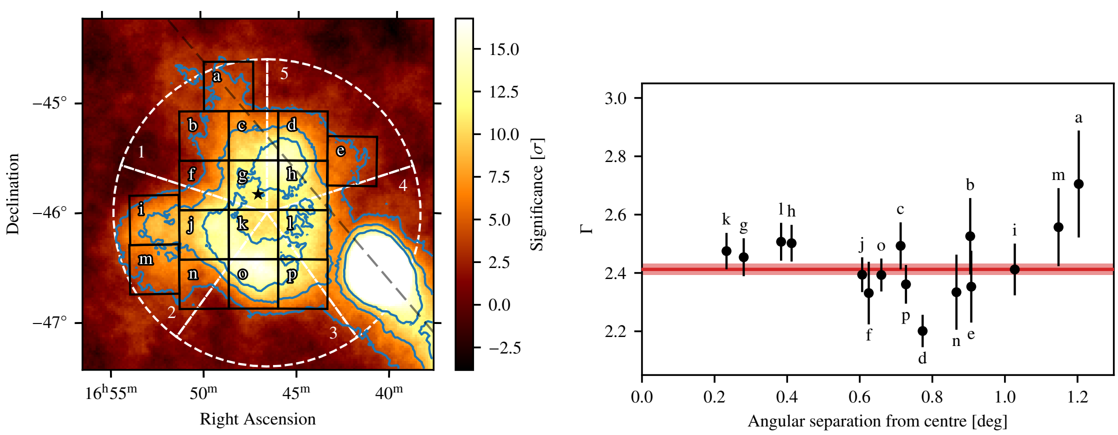


(a) (b)

Figure 1: (a) Flux map showing the γ-ray emission around the young massive stellar cluster Westerlund 1. The black star marks the position of Westerlund 1, the grey dashed line the Galactic plane. The dark grey symbols denote positions of sources from the *Fermi*-LAT 4FGL-DR2 catalogue [17,18]. The white circle shows the position with respect to which the radial profiles in the right-hand panel have been computed. (b) Radial profiles of the γ-ray excess. The thick black curve shows the total emission and the coloured curves are for different energy bands. The profiles have been normalised so that they can directly be compared.

To study the energy spectrum of HESS J1646−458, we defined 16 square 'signal regions', labelled a–p (see Fig. 2(a)), for which we extracted separate spectra. For each region, we fitted the γ-ray excess with a power-law model, $\mathrm{d}N/\mathrm{d}E \propto (E/1\,\mathrm{TeV})^{-\Gamma}$, where Γ denotes the power-law spectral index. In Fig. 2(b), we show the spectral indices for all regions as a function of their separation from the centre point (white circle in Fig. 1(a)). No trend can be made out, implying that the energy spectra in the 16 signal regions are very similar to each other – a confirmation of our previous finding that the morphology of HESS J1646−458 does not change with energy.



(a) (b)

Figure 2: (a) Significance map showing the definition of 'signal regions' that are used for spectrum extraction. (b) Fitted power-law spectral index Γ in each region as a function of the distance from the centre point.

To obtain a combined energy spectrum for HESS J1646−458, we summed the flux points extracted for all signal regions; the result is shown by the black points in Fig. 3. Remarkably, the combined spectrum extends to several tens of TeV, revealing that Westerlund 1 must be a powerful cosmic-ray accelerator. Fitting the combined flux points with a power-law model with exponential cut-off (ECPL), $\mathrm{d}N/\mathrm{d}E \propto (E/1\,\mathrm{TeV})^{-\Gamma} \cdot \exp(-E/E_c)$, we obtained a spectral index of $\Gamma = 2.30 \pm 0.04$ and a cut-off energy of $E_c = (44^{+17}_{-11})$ TeV. Additionally, we employed the `Naima` package [19] to fit a hadronic (proton-proton) and a leptonic (inverse Compton) model to the flux points. For the hadronic model, we obtained a primary proton spectrum with index $\Gamma_p = 2.33 \pm 0.06$ and cut-off energy $E_c^p = (400^{+250}_{-130})$ TeV. The total required energy in protons above an energy of 1 GeV is $W_p = 6 \times 10^{51} (n/1\,\mathrm{cm}^{-3})^{-1}$ erg, where n is the density of the ambient medium. For the leptonic model, we obtained a primary electron spectrum with index $\Gamma_e = 2.97 \pm 0.07$ and cut-off energy $E_c^e = (180^{+200}_{-70})$ TeV, where we have used a target photon field related to the stellar cluster in addition to the usually adopted infrared and cosmic microwave background photon fields (see [9] for details). The required luminosity in electrons above 0.1 TeV is at least $L_e > 4.1 \times 10^{35}\,\mathrm{erg\,s^{-1}}$, and increases in the presence of magnetic fields to due synchrotron losses of the electrons.

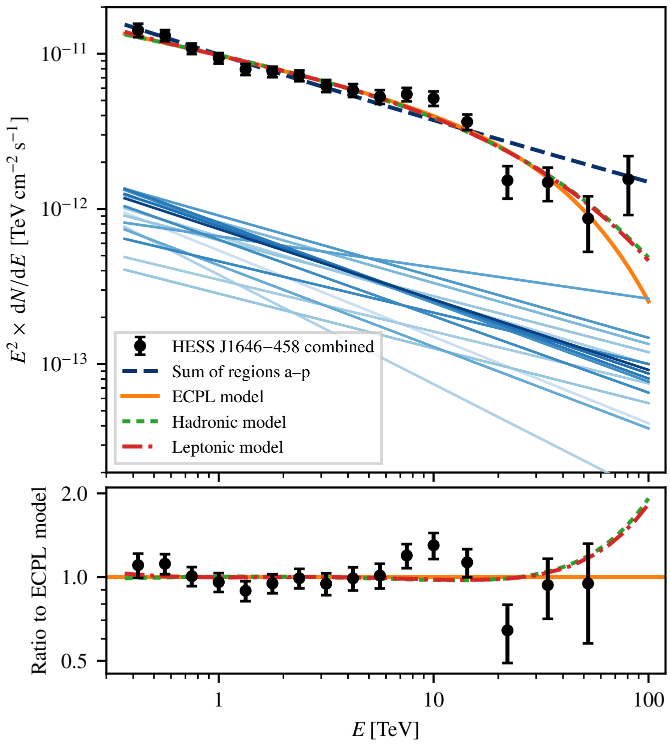


Figure 3: Combined energy spectrum of HESS J1646−458. The solid orange, dashed green, and dashed-dotted red lines show model curves fitted to the data points. Fitted power law models for each signal region are displayed by solid blue lines, where darker shades indicate a closer proximity to Westerlund 1. The dashed blue line denotes the sum over all signal regions. The bottom panel shows the ratio to the fitted ECPL model (orange line).

To explore the feasibility of a hadronic scenario, in which the γ-ray emission is due to interactions of cosmic-ray nuclei with ambient matter, we searched for a correlation between the γ-ray emission and hydrogen gas as indicated by radio line emission surveys. Specifically, we used the

SGPS H I survey [20] to infer the presence of atomic hydrogen gas and the Mopra ^{12}CO survey [21] as a tracer for molecular hydrogen. In Fig. 4, we show the resulting maps of the H I and CO emission in the vicinity of Westerlund 1, and compare them to the γ-ray emission. Both the H I and CO map show that hydrogen is in principle present in the region. Indeed, we obtained an average gas density of $\sim$10 cm^{-3} for the whole region. However, in particular the molecular gas is distributed very inhomogeneously, and the maps indicate that the gas density is low in regions with bright γ-ray emission. This presents a challenge for the hadronic scenario. Nevertheless, the scenario cannot be ruled out, as the estimates of gas distributions are afflicted with substantial systematic uncertainties (e.g. part of the gas is expected to be ionised due to the ultraviolet radiation from the stellar cluster), and because the underlying distribution of cosmic rays need not be uniform.

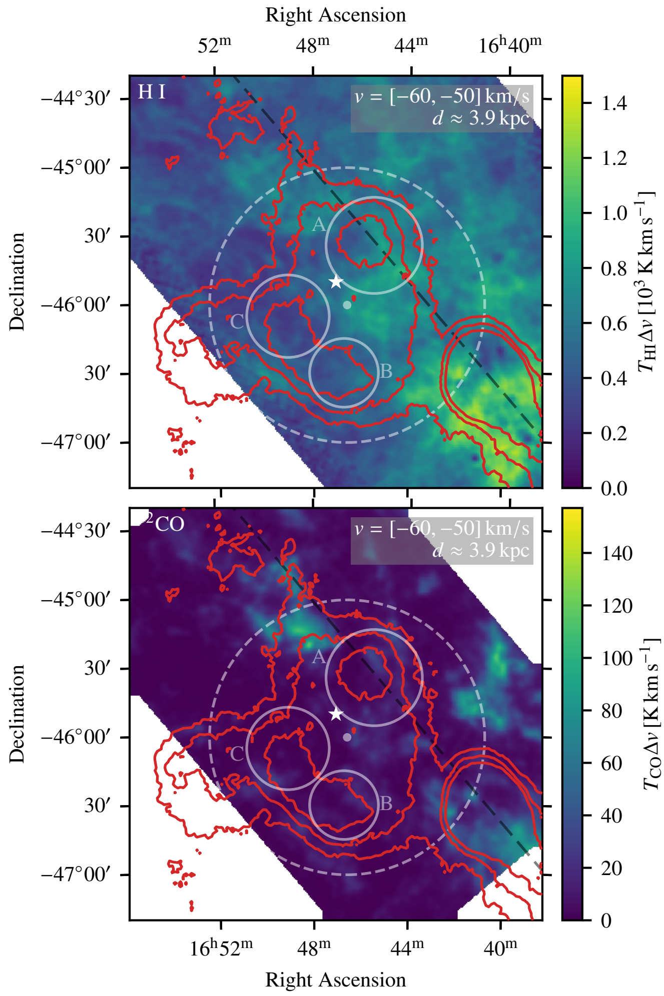


Figure 4: Maps showing H I emission (top panel; [20]) and ^{12}CO emission (bottom panel; [21]) in the region around Westerlund 1. Both show the emission for a velocity interval of $v = [-60, -50]$ km s^{-1}, which approximately corresponds to a distance of 3.9 kpc. The white star marks the position of Westerlund 1, the grey dashed line the Galactic plane. The red contour lines are from the γ-ray flux map shown in Fig. 1(a).

4. Discussion

Based on the lack of energy-dependent morphology of HESS J1646−458 and the required energetics to explain the γ-ray emission, we conclude that only Westerlund 1 can explain the majority of the emission. Various possibilities for the acceleration site of the cosmic rays exist:

- **Acceleration within the cluster.** Acceleration within the cluster could happen at shock fronts that form in the interaction of the stellar winds of the massive stars inside the cluster, or in the interaction of a supernova shock wave with a stellar wind. The lack of energy-dependent morphology rules out a leptonic scenario, as a steepening of the spectrum towards larger radii would be expected in this case. A hadronic scenario is in principle viable energetically, but requires the presence of multi-PeV protons within the cluster to overcome inevitable adiabatic losses during propagation.

- **Acceleration in turbulent superbubble.** In this scenario, cosmic rays are accelerated via stochastic scattering on magnetic turbulence inside the superbubble blown by the collective cluster wind (see e.g. [4]). However, basic superbubble models suggest that for Westerlund 1, the bubble should have a radius of $O(180\,\mathrm{pc})$, which is much larger than the observed γ-ray emission. An outer shock at such a large radius has also not been observed at other wavelengths, which makes this possibility seem unfavoured. On the other hand, the evolution of superbubbles is a complex process that may in reality develop differently than predicted by basic models.

- **Acceleration at cluster wind termination shock.** For a sufficiently compact cluster, the collective cluster wind is expected to form a termination shock, which has been proposed as an efficient cosmic-ray acceleration site (e.g. [3]). Intriguingly, basic superbubble models suggest that the termination shock for Westerlund 1 should lie at a radius of $O(30\,\mathrm{pc})$, which matches the radius of the observed shell-like structure in the γ-ray emission. A hadronic scenario would work energetically, but require the presence of a relatively strong magnetic field ($O(50\,\mu\mathrm{G})$) in order to confine the cosmic rays for long enough. Interestingly, an acceleration at the termination shock also renders a leptonic scenario feasible, as the acceleration site naturally explains the complex structure of the γ-ray emission. In this case, the magnetic field should be low enough ($B \lesssim 10\,\mu\mathrm{G}$) so that the electrons do not radiate too much synchrotron emission.

While neither of the above possibilities can be ruled out, the fact that the observed radius of the shell-like structure in the γ-ray emission coincides with the predicted radius of the cluster wind termination shock could be a tantalising hint.

5. Conclusion

We have presented the results of a recent study of the γ-ray emission of HESS J1646−458, which surrounds the young massive stellar cluster Westerlund 1 [9].

HESS J1646−458 is a largely extended (~2°) γ-ray source with a very complex morphology. The γ-ray emission exhibits a shell-like structure that does not seem to depend on energy. The combined energy spectrum extends to at least several tens of TeV.

Detailed investigations of possible counterparts have shown that only the young massive stellar cluster Westerlund 1 can explain the majority of the emission – revealing it as a powerful cosmic-ray accelerator. While the exact acceleration site and mechanism could not be determined unambiguously, the H.E.S.S. results provide important new constraints for models of cosmic-ray acceleration in massive stellar clusters. The observed shell-like structure of the emission could hint at cosmic rays being accelerated at the termination shock of the collective cluster wind.

In conclusion, the study of Westerlund 1 has shown that young massive stellar clusters likely contribute to the flux of Galactic cosmic rays. However, to quantitatively assess their contribution, a better understanding of the exact acceleration mechanism and studies of further clusters are necessary.

References

[1] C.J. Cesarsky and T. Montmerle, *Gamma rays from active regions in the galaxy: The possible contribution of stellar winds*, *Space Sci. Rev.* **36** (1983) 173.

[2] F. Aharonian, R. Yang and E. de Oña Wilhelmi, *Massive stars as major factories of Galactic cosmic rays*, *Nat. Astron.* **3** (2019) 561 [1804.02331].

[3] G. Morlino, P. Blasi, E. Peretti and P. Cristofari, *Particle acceleration in winds of star clusters*, *MNRAS* **504** (2021) 6096 [2102.09217].

[4] T. Vieu, S. Gabici, V. Tatischeff and S. Ravikularaman, *Cosmic ray production in superbubbles*, *MNRAS* **512** (2022) 1275 [2201.07488].

[5] J.S. Clark, I. Negueruela, P. Crowther and S.P. Goodwin, *On the massive stellar population of the super star cluster Westerlund 1*, *A&A* **434** (2005) 949 [astro-ph/0504342].

[6] I. Negueruela, E.J. Alfaro, R. Dorda, A. Marco, J. Maíz Apellániz and C. González-Fernández, *Westerlund 1 under the light of Gaia EDR3: Distance, isolation, extent, and a hidden population*, *A&A* **664** (2022) A146 [2204.00422].

[7] W. Brandner, J.S. Clark, A. Stolte, R. Waters, I. Negueruela and S.P. Goodwin, *Intermediate to low-mass stellar content of Westerlund 1*, *A&A* **478** (2008) 137 [0711.1624].

[8] A. Abramowski et al. (H.E.S.S. Collaboration), *Discovery of extended VHE γ-ray emission from the vicinity of the young massive stellar cluster Westerlund 1*, *A&A* **537** (2012) A114 [1111.2043].

[9] F. Aharonian et al. (H.E.S.S. Collaboration), R. Blackwell, C. Braiding, M. Burton, K. Cubuk, M. Filipović et al., *A deep spectromorphological study of the γ-ray emission surrounding the young massive stellar cluster Westerlund 1*, *A&A* **666** (2022) A124 [2207.10921].

[10] F. Aharonian et al. (H.E.S.S. Collaboration), *Observations of the Crab nebula with HESS*, *A&A* **457** (2006) 899 [astro-ph/0607333].

[11] C. van Eldik, M. Holler, D. Berge, D. Zaborov, J.-P. Lenain, V. Marandon et al., *Observations of the Crab Nebula with H.E.S.S. phase II*, in *Proc. 34th Int. Cosmic Ray Conf. — PoS(ICRC2015)*, vol. 236, p. 847, 2016, DOI [1509.02902].

[12] S. Ohm, C. van Eldik and K. Egberts, *γ/hadron separation in very-high-energy γ-ray astronomy using a multivariate analysis method*, *Astropart. Phys.* **31** (2009) 383 [0904.1136].

[13] R.D. Parsons and J.A. Hinton, *A Monte Carlo template based analysis for air-Cherenkov arrays*, *Astropart. Phys.* **56** (2014) 26 [1403.2993].

[14] C. Deil, J. Lefaucheur, R. Zanin, C. Boisson, B. Khelifi, R. Terrier et al., *Gammapy - A prototype for the CTA science tools*, in *Proc. 35th Int. Cosmic Ray Conf. — PoS(ICRC2017)*, vol. 301, p. 766, 2017, DOI [1709.01751].

[15] C. Deil, A. Donath, R. Terrier et al., *Gammapy: v0.17*, *Zenodo* (2020) .

[16] L. Mohrmann, A. Specovius, D. Tiziani, S. Funk, D. Malyshev, K. Nakashima et al., *Validation of open-source science tools and background model construction in γ-ray astronomy*, *A&A* **632** (2019) A72 [1910.08088].

[17] S. Abdollahi et al. (*Fermi*-LAT Collaboration), *Fermi Large Area Telescope Fourth Source Catalog*, *ApJS* **247** (2020) 33 [1902.10045].

[18] J. Ballet, T.H. Burnett, S.W. Digel and B. Lott, *Fermi Large Area Telescope Fourth Source Catalog Data Release 2*, *ArXiv e-prints* (2020) [2005.11208].

[19] V. Zabalza, *Naima: a Python package for inference of particle distribution properties from nonthermal spectra*, in *Proc. 34th Int. Cosmic Ray Conf. — PoS(ICRC2015)*, vol. 236, p. 922, 2016, DOI.

[20] N.M. McClure-Griffiths, J.M. Dickey, B.M. Gaensler, A.J. Green, M. Haverkorn and S. Strasser, *The Southern Galactic Plane Survey: H I Observations and Analysis*, *ApJS* **158** (2005) 178 [astro-ph/0503134].

[21] C. Braiding, G.F. Wong, N.I. Maxted, D. Romano, M.G. Burton, R. Blackwell et al., *The Mopra Southern Galactic Plane CO Survey—Data Release 3*, *PASA* **35** (2018) e029 [1902.04249].