Abstract. In this paper the current status of γ-ray observations of starburst galaxies from hundreds of MeV up to TeV energies with space-based instruments and ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs) is summarised. The properties of the high-energy (HE; $100\text{MeV} \leq E \leq 100\text{GeV}$) and very-high-energy (VHE; $E \geq 100\text{GeV}$) emission of the archetypical starburst galaxies M 82 and NGC 253 are discussed and put into context with the HE γ-ray emission detected from other galaxies that show enhanced star-formation activity such as NGC 4945 and NGC 1068. Finally, prospects to study the star-formation – γ-ray emission connection from Galactic systems to entire galaxies with the forthcoming Cherenkov Telescope Array (CTA) are outlined.

Keywords: Galaxies: starburst, Gamma rays: galaxies, Radiation mechanisms: non-thermal

PACS: 98.54.Ep

INTRODUCTION

Starburst galaxies have exceptionally high star-formation rates (SFRs) in very localised regions (also called starburst region) that have typical sizes of hundreds of parsecs. In these regions, the high SFR leads to an increased formation of massive stars and hence supernova explosion rate compared to the rest of the galaxy. The high thermal pressure in the central regions often leads to the formation of a starburst wind. More than 20 years ago, it has been proposed that starburst galaxies could be sources of HE and VHE γ-ray emission [e.g. 1, 2]. The basic idea is that particles are accelerated in the numerous supernova remnant (SNR) shock waves, escape into the starburst region and interact with radiation fields, magnetic fields and with the dense gas. Electrons (and positrons) predominantly lose energy via inverse Compton and synchrotron processes, whereas accelerated protons (and heavier nuclei) predominantly lose energy in proton-proton interactions in which they produce neutral and charged pions which can decay into e.g. electrons (positrons) and γ-rays, respectively.

The detection of HE and VHE γ-ray emission from the archetypical starburst galaxies M 82 and NGC 253 with the Fermi-LAT, VERITAS and H.E.S.S. instruments [3, 4, 5] has triggered a lot of theoretical work. These studies are aiming to explain the origin and properties of the γ-ray emission in different scenarios. Most calculations [see e.g. 6, 7, 8, 9] consider diffuse γ-ray emission from inelastic proton-proton interactions and subsequent π0-decay as leading loss mechanism, although it has recently been shown that individual sources such as pulsar wind nebulae (PWNe) could significantly contribute to the γ-ray signal [10, 11].

The first part of this work focuses on the connection between massive star formation and γ-ray emission in individual Galactic γ-ray sources and links these to galaxy-size systems such as starburst galaxies. The spatial and spectral properties of the γ-ray
emission from NGC 253 and M 82 and implications for the origin of the emission are discussed in more detail in the second part of this paper. In the third section the \( \gamma \)-ray emission from the starburst galaxies with Seyfert 2 nuclei NGC 4945 and NGC 1068 is addressed. Finally, the \( \gamma \)-ray emission from other Local Group galaxies is discussed and prospects for the Cherenkov Telescope Array (CTA) to investigate the connection between massive star formation and high-energy particles on all spatial scales is outlined.

**STAR-FORMATION AND \( \gamma \)-RAY EMISSION ON DIFFERENT SPATIAL SCALES**

At TeV energies, the population of Galactic VHE \( \gamma \)-ray sources clusters tightly along the Galactic plane. It has a scale height similar to that of molecular gas and traces regions of massive star formation. Although \( \sim 1/3 \) of the source population is still unidentified and lacks counterparts at lower energies, the majority of TeV sources is coincident with PWNe, SNRs, SNRs interacting with molecular clouds or stellar clusters [e.g. 12, 13, 14, 15]. At GeV energies, more and more of the objects that show bright TeV emission also emerge as HE \( \gamma \)-ray sources in the Fermi-LAT energy band. Especially sources coincident with regions of active star formation show \( \gamma \)-ray spectra that smoothly connect from hundreds of MeV to multi-TeV energies. The most prominent sources, where such spectra are observed are SNRs at different evolutionary stages that interact with molecular clouds, e.g. W28 [16, 17], W49 [18, 19], W51C [20, 14] or IC443 [21, 22]. The preferred interpretation of the \( \gamma \)-ray emission in these systems is that protons interact with the dense gas and produce \( \pi^0 \)-decay \( \gamma \)-ray emission.

The progenitors of massive stars that undergo supernova explosions at the end of their lives typically form and evolve in associations or stellar clusters. In stellar clusters, the fast winds of massive stars can merge and/or interact with the SNR shock fronts forming a collective bubble or even a superbubble. Existing shocks get further amplified and particles can get accelerated to very high energies [e.g. 23, 24]. H.E.S.S. observations of the massive stellar cluster Westerlund 1 revealed an emission region \( \sim 20 \) times the size of the cluster [15]. A very modest amount of energy injected by the numerous supernovae that exploded over the past millions of years and the collective stellar winds can easily explain the emission level. The morphology and spectrum of the VHE emission suggests that a significant part of the non-thermal particles originate from Westerlund 1, and that protons are likely responsible for the emission. At GeV energies, three of the four HE \( \gamma \)-ray sources that are coincident with the TeV emission are marked as possibly confused with Galactic diffuse emission, indicating that they might physically be connected and possibly associated to the H.E.S.S. emission [25]. Future studies will show whether or not the GeV and TeV emission is indeed related and how particle acceleration, particle escape and interaction with the surrounding material of Westerlund 1 works in detail. The recent detection of HE \( \gamma \)-ray emission from the vicinity of the Cygnus superbubble with the Fermi-LAT between 1 GeV and 100 GeV further supports the idea of particle acceleration in stellar clusters and superbubbles [26]. Also in this case the morphology and spectrum (that is consistent with an extrapolation to the measurement by Milagro [27]) suggests that protons are responsible for the non-thermal emission.
In summary, the study of $\gamma$-ray emission from SNRs interacting with molecular clouds, stellar clusters and superbubbles with Cherenkov telescopes and the Fermi-LAT provided strong evidence for proton acceleration in regions of massive star formation. All these Galactic systems show $\gamma$-ray emission on spatial scales from tens of parsecs up to $\sim$ 100 parsec. The $\gamma$-ray emission from starburst nuclei can be used to investigate the connection between massive star formation and non-thermal particles on hundreds of parsec scales and to study populations of particle accelerators. It is complementary to observations of individual Galactic objects and a powerful tool to probe the paradigm of cosmic-ray acceleration in SNR shells.

$\gamma$-RAY OBSERVATIONS OF STARBURST GALAXIES

The detection of VHE $\gamma$-ray emission from the starburst galaxies NGC 253 and M 82 using ground-based Cherenkov telescopes has been reported in 2009 by the H.E.S.S. [5] and VERITAS collaborations [4], respectively. Both galaxies are right at the sensitivity limit of current generation IACTs and it required more than 100 hours of good-quality data to establish these objects as TeV $\gamma$-ray emitters. M 82 and NGC 253 are the first two external galaxies that have been detected in VHE $\gamma$-rays where the emission is not powered by a supermassive black hole (as opposed to e.g. Active Galactic Nuclei or radio galaxies). Shortly after the detection at TeV energies, the Fermi-LAT collaboration announced the discovery of these two starburst galaxies at GeV energies [3]. Also the HE $\gamma$-ray signals are very weak and $\approx$ 11 months of LAT data were required to detect M 82 and NGC 253 between a few hundred MeV and a couple of GeV energies. No indication of variability at any $\gamma$-ray energy could be detected from both starbursts, supporting the idea that the emission is not triggered by a supermassive black hole at the centres of the galaxies. In the following the observational properties of the $\gamma$-ray emission from NGC 253 and M 82 are presented and the implications for the origin of the emission are outlined. A more detailed discussion of theoretical implications of the $\gamma$-ray emission from starburst galaxies can be found in these proceedings [29].

NGC 253

Based on 30 months of LAT data and $\approx$ 180 hours of good-quality H.E.S.S. data, [9] presented a detailed analysis of the $\gamma$-ray emission from NGC 253. The angular extension of NGC 253 of $\approx$ 30' x 7' makes it possible to disentangle the TeV signal from the disc of the galaxy and the starburst nucleus. Indeed, the upper limit on the extension of the TeV emission of $<2.4'(3\sigma)$ implies that the VHE $\gamma$-ray emission is consistent with originating in the starburst nucleus. This is also visible in Figure 1, where no significant disc component in NGC 253 is seen at TeV energies. Due to the limited angular resolution of the LAT, such a discrimination is not possible at GeV energies. The best fit position of Fermi is however consistent with the best fit position of H.E.S.S. and the optical centre of the galaxy [9].

The large data sets gathered in HE and VHE $\gamma$-rays allowed to study the spectrum of the $\gamma$-ray emission in great detail. The Fermi spectrum between 0.2 GeV and 200 GeV
FIGURE 1. H.E.S.S. sky map of NGC 253 (right, [9]). The zoom into the central part shown at the top left is a composite image with optical in red (ESO/DSS), near-infrared in green (2MASS, Ks band) and VHE $\gamma$-rays in blue (H.E.S.S.). The zoom on the bottom left shows the central molecular zone of NGC 253 in molecular line emission [28] (Reproduced by permission of the AAS).

is best described by a power law in energy with index $\Gamma_{\text{HE}} = 2.24 \pm 0.14_{\text{stat}} \pm 0.03_{\text{sys}}$. The H.E.S.S. best fit spectral index above the energy threshold of 220 GeV is $\Gamma_{\text{VHE}} = 2.14 \pm 0.18_{\text{stat}} \pm 0.30_{\text{sys}}$ and hence compatible within statistical errors with the LAT index. Interestingly, a combined fit of the Fermi and H.E.S.S. spectrum over four decades in energy results in a photon index of $\Gamma = 2.34 \pm 0.03$ and a fit probability of 30%. In case the emission is of hadronic origin, and assuming canonical values for the supernova explosion energy $E_{\text{SN}} = 10^{51}$ erg and conversion efficiency to cosmic rays $E_{\text{SN}} \rightarrow E_{\text{CR}} = 10\%$, the measured $\gamma$-ray flux suggests that $\approx 20 - 30\%$ of the protons interact with the dense material in the starburst region before leaving the system in the starburst wind. Although the available statistics is quite limited, the smooth alignment of the GeV and TeV spectrum is suggestive of the fact that one energy loss mechanism dominates from hundreds of MeV up to several TeV. In this interpretation energy-dependent diffusion would play a minor role and (energy-independent) escape of particles from the starburst nucleus and proton-proton collisions would be the dominant energy loss mechanisms of the cosmic-ray population in the starburst of NGC 253.

M 82

M 82 is with an apparent size of $\approx 11' \times 4'$ significantly smaller than NGC 253. It is hence challenging to discriminate the starburst contribution of the HE and VHE $\gamma$-ray emission detected by the LAT and VERITAS from the disc of the galaxy [3, 4]. However, as for NGC 253, the GeV and TeV emission is consistent with originating from
FIGURE 2. $\gamma$-ray luminosity spectra of SNRs interacting with molecular clouds and the Cygnus superbubble (left) and of star-forming galaxies (right). GeV data has been obtained with Fermi, distances used to calculate the luminosities are given in [17, 20, 22, 26, 32]. TeV data for W28 is from H.E.S.S. [16], for W51 from MAGIC [14], for Cygnus from Milagro [27] and for IC 443 from VERITAS [21].

a point-like source located in the starburst core of M 82. Based on three years of LAT data, the $\gamma$-ray spectrum of M 82 between 100 MeV and 100 GeV can be described by a power law with spectral index $\Gamma_{\text{HE}} = 2.2 \pm 0.1_{\text{stat}}$. The measured VERITAS spectrum obtained with a total of $\approx 140$ hours of good quality data has an index of $\Gamma_{\text{VHE}} = 2.5 \pm 0.6_{\text{stat}} \pm 0.2_{\text{sys}}$, and is within large statistical errors consistent with the Fermi index and extrapolated Fermi flux. Within errors, also the flux from M 82 at GeV and TeV energies is comparable to the flux measured from NGC 253.

NGC 4945 and NGC 1068

Similar to the two starburst galaxies discussed in the previous chapter, also NGC 4945 and NGC 1068 are galaxies with circumnuclear starbursts. These two objects however also have radio-quiet obscured Active Galactic Nuclei (AGN). In 2010, both galaxies were reported to emit HE $\gamma$-rays [30, 31]. Using three years of LAT data, [32] analysed the spectrum in more detail and reconstructed a spectral index of $\Gamma_{\text{HE}} = 2.1 \pm 0.2$ and $\Gamma = 2.2 \pm 0.2$ for NGC 4945 and NGC 1068, respectively. The spectra as shown in Figure 2 (right) are similar to those of M 82 and NGC 253 and other Local Group galaxies such as M 31 or the Large Magellanic Cloud (LMC). So far, no TeV emission from these two Seyfert galaxies has been reported, although a detection is within reach of current generation IACTs. The HE $\gamma$-ray emission from NGC 4945 and NGC 1068 could have their origin in the starburst and/or a possible AGN activity. One way to disentangle these components is to study the $\gamma$-ray lightcurve, as the starburst emission is expected to be non-variable. Although statistics is limited, the GeV lightcurves of NGC 4945 and NGC 1068 show no indication for variability, which could point towards a starburst origin of the $\gamma$-ray emission. A second possibility is to compare the star-formation rate and available target material in these systems with the observed $\gamma$-ray luminosity. In the case of NGC 4945, the level of observed $\gamma$-ray emission is consistent with the estimated supernova rate. Together with the non-variable signal this implies
that the starburst activity alone can account for the observed GeV signal. Although the supernova rate in NGC 1068 is comparable to the ones estimated for M 82 and NGC 253 the observed radio and γ-ray fluxes are an order of magnitude higher. This suggests that the AGN component might dominate over a possible starburst activity at these wavelengths. However, apart from NGC 4945 and NGC 1068, no other Seyfert galaxy with radio-quiet AGN was observed to emit HE γ-rays, with upper limits up to one order of magnitude below the level seen for NGC 1068 [e.g. 33]. Whether the observed emission from these two Seyfert galaxies is indeed related to the star-formation process or if it is rather driven by AGN activity requires further monitoring by the LAT and search for possible variability as well as TeV observations and more detailed modelling of the spectral energy distributions.

γ-RAY OBSERVATIONS OF LOCAL GROUP GALAXIES

Starburst galaxies are not the only galaxies that have been observed to emit γ-rays. Firstly, the Milky Way itself is a very strong source of diffuse HE γ-ray emission, originating mainly from cosmic-rays that illuminate the Galactic interstellar medium and lose energy via Bremsstrahlung and inverse Compton processes as well as pion-production and decay. Also the Milky Way satellites, the LMC [34] and the Small Magellanic Cloud (SMC, [35]) have been detected with the LAT. Moreover, the Andromeda galaxy (M 31, [36]) has been reported to emit GeV γ-rays. The same authors found a simple scaling relation of SFR and γ-ray luminosity for these Local Group galaxies that also extents to NGC 253 and M 82. [32] used a larger 3-year Fermi data set and examined the γ-ray properties of 69 dwarf, spiral, luminous and ultra-luminous galaxies in GeV γ-rays. A quasi-linear scaling relation between γ-ray luminosity and the SFR as traced by infrared and radio continuum emission further supports the relation between massive star formation and high-energy particles. Interestingly, there is a spread of one order of magnitude in this correlation that could point towards differences in e.g. the efficiency with which massive stars via e.g. supernovae transfer energy into non-thermal particles, how high-energy particles interact with the surrounding material and/or how they escape without interaction. [32] conclude that between 4% and 23% of the intensity of the isotropic diffuse component as measured with Fermi could be accounted for by unresolved star-forming galaxies between redshift 0 ≤ z ≤ 2.5. Furthermore, up to ten galaxies might be detectable within ten years of operation.

PROSPECTS FOR CTA

Figure 2 (left) shows the γ-ray spectra of three prominent SNRs that are interacting with molecular clouds and the spectrum of the superbubble in the Cygnus region. For all these sources, hadronic emission scenarios are favoured over leptonic scenarios. The same is true for the γ-ray spectra and the emission from star-forming galaxies as shown in Figure 2 (right). Especially the smooth connection of GeV and TeV spectra of individual Galactic objects and the diffuse emission from e.g. NGC 253 and M 82 is striking. So far, the correlation between star-formation and γ-ray emission has only be
studied for GeV-detected galaxies. At TeV energies, only the two archetypical starburst galaxies have been detected and no emission from M 31, the LMC, SMC or the Milky Way has been reported. This situation will change once CTA is in operation [38]. CTA will deliver an order of magnitude better sensitivity, a factor $\sim 5$ better point spread function and broader energy coverage and will allow to study individual objects and populations of sources in unprecedented detail. First of all, it will be possible to probe whether or not the NGC 253 TeV emission is point-like or if it has an extension, similar to the spatial extent of the central molecular zone in the starburst region. Secondly, it might be possible to detect the disc of NGC 253 in TeV $\gamma$-rays in a deep exposure, as the expected flux is about one order of magnitude lower than the starburst emission [e.g. 9]. Furthermore, the $\gamma$-ray spectrum will be measured with very good accuracy and to lower energies, allowing to investigate if spectral features arise that indicate a change in the dominant energy-loss mechanism, or if significant signatures for $\gamma-\gamma$ pair production or a dominance of PWNe at TeV energies become apparent. As for NGC 253, also the M 82 $\gamma$-ray spectrum will be studied in great detail and different emission scenarios can be tested. All other Local Group galaxies that have been detected with Fermi can also be studied with CTA and the SFR – $\gamma$-ray luminosity relation can be probed with these systems at TeV energies. Finally, it will be possible to study the whole young Galactic SNR population with CTA [39]. With the detailed understanding of how particle acceleration, escape, and interaction with the surrounding medium works, it might be possible to get insights on how the star-formation process is linked to high-energy particles. The study of superbubbles with CTA might provide the link between individual $\gamma$-ray emitting SNRs and the emission from starburst galaxies.

ACKNOWLEDGMENTS

S.O. acknowledges the support of the Humboldt foundation by a Feodor-Lynen research fellowship.

REFERENCES

1. Völk, H. J., Klein, U. and Wielebinski, R., A&A, 213, 12 (1989)
2. Akyuz, A., Brouillet, N. and Ozel, M. E., A&A, 248, 419 (1991)
3. Abdo, A. A., et al. (Fermi-LAT Collaboration), ApJL, 709, 152 (2010a)
4. Acciari, V. A., et al. (VERITAS Collaboration), Nature, 462, 770 (2009)
5. Acero, F., et al. (H.E.S.S. Collaboration), Science, 326, 1080 (2009)
6. Lacki, B. C., Thompson, T. A., Quataert, E., Loeb, A. and Waxman, E., ApJ, 734, 107 (2011)
7. Ohm, S. and Hinton, J., The Spectral Energy Distribution of Galaxies, Proceedings of the International Astronomical Union, IAU Symposium, 284, 382 (2012)
8. Paglione, T. A. D. and Abrahams, R. D., ApJ, 755, 106 (2012)
9. Abramowski, A., et al. (H.E.S.S. Collaboration), ApJ, 757, 158 (2012)
10. Mannheim, K., Elsässer, D. and Tibolla, O., Astroparticle Physics, 35, 797 (2012)
11. Ohm, S. and Hinton, J. A., submitted to MNRAS Letters (2012)
12. Aharanion, F., et al. (H.E.S.S. Collaboration), A&A, 460, 365 (2006)
13. Acero, F., et al. (H.E.S.S. Collaboration), A&A, 516, 62 (2010)
14. Aleksic, J., et al. (MAGIC Collaboration), A&A, 541, 13 (2012)
15. Abramowski, A., et al. (H.E.S.S. Collaboration), A&A, 537, 114 (2012)
16. Aharonian, F., et al. (H.E.S.S. Collaboration), A&A, 481, 401 (2008)
17. Abdo, A. A., et al. (Fermi-LAT Collaboration), ApJ, 718, 348 (2010b)
18. Abdo, A. A., et al. (Fermi-LAT Collaboration), ApJ, 722, 1303 (2010c)
19. Brun, P., et al. (H.E.S.S. Collaboration), Proceedings of Science, arXiv:1104.5003 (2011)
20. Abdo, A. A., et al. (Fermi-LAT Collaboration), ApJ, 706, 1 (2009)
21. Albert, J., et al. (MAGIC Collaboration), ApJ, 664, 87 (2007)
22. Abdo, A. A., et al. (Fermi-LAT Collaboration), ApJ, 712, 459 (2010d)
23. Bykov, A. M., Space Science Reviews, 99, 317 (2001)
24. Parizot, E., et al., A&A, 424, 747 (2004)
25. Nolan, P. L., et al. (Fermi-LAT Collaboration), ApJS, 199, 31 (2012)
26. Abdo, A. A., et al. (Fermi-LAT Collaboration), Science, 334, 1103 (2011)
27. Abdo, A. A., et al. (Milagro Collaboration), ApJ, 658, 33 (2007)
28. Sakamoto, K., et al., ApJ, 735, 19 (2011)
29. Lacki, B. C., these proceedings (2012)
30. Abdo, A. A., et al. (Fermi-LAT Collaboration), ApJS, 188, 405 (2010e)
31. Lenain, J.-P., et al., A&A, 524, 72 (2010)
32. Ackermann, M., et al. (Fermi-LAT Collaboration), ApJ, 755, 164 (2012a)
33. Ackermann, M., et al. (Fermi-LAT Collaboration), ApJ, 747, 104 (2012b)
34. Abdo, A. A., et al. (Fermi-LAT Collaboration), A&A, 512, 7 (2010f)
35. Abdo, A. A., et al. (Fermi-LAT Collaboration), A&A, 523, 46 (2010g)
36. Abdo, A. A., et al. (Fermi-LAT Collaboration), A&A, 523, 2 (2010h)
37. Acciari, V. A., et al. (VERITAS Collaboration), ApJ, 698, 133 (2009)
38. Actis, M., et al. (CTA Collaboration), Exp Astron, 32, 193 (2011)
39. Acero, F., et al. (CTA Collaboration), accepted for publication in Astroparticle Physics, arXiv:1209.0582, (2012)