The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus
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TeV observations of the Galactic center and starburst galaxies

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Abstract. The vicinity of the Galactic center harbors many potential accelerators of cosmic rays (CR) that could shine in very-high-energy (VHE) γ-rays, such as pulsar wind nebulae, supernova remnants, binary systems and the central black hole Sgr A*, and is characterized by high gas density, large magnetic fields and a high rate of starburst activity similar to that observed in the core of starburst galaxies. In addition to these astrophysical sources, annihilation of putative WIMPs concentrated in the gravitational well could lead to significant high-energy emission at the Galactic center. The Galactic center region has been observed by atmospheric Cherenkov telescopes, and in particular by the H. E. S. S. array in Namibia for the last ten years above 150 GeV. This large data set, comprising more than 200 hours of observations, led to the discovery of a point-like source spatially compatible with the supermassive black hole Sgr A*, and to an extended diffuse emission, correlated with molecular clouds and attributed to the interaction of cosmic rays with the interstellar medium. Over the same time period, two starburst galaxies, namely M 82 and NGC 253, were detected at TeV energies after very deep exposures. Results from these ten years of observations of the Galactic center region and starburst galaxies at TeV energies are presented, and implications for the various very-high-energy emission mechanisms are discussed.

Keywords. IACT, TeV, Starburst Galaxies, Sgr A*

1. Introduction

The Galactic center (GC) is a very complex region crowded with astrophysical sources that can potentially emit high energy (HE, $100\,\mathrm{MeV} < E < 100\,\mathrm{GeV}$) and very high energy (VHE, $E > 100\,\mathrm{GeV}$) γ-rays. In addition to the strong source confusion problems caused by the limited angular resolution of the instruments operating in these energy regimes, the center is hidden in the optical and ultraviolet wavelengths by dense molecular clouds. For a review of the GC region, see e.g. Melia and Falcke (2001).

The Galactic center harbors a $4 \times 10^6\,\mathrm{M}_\odot$ black hole coincident with the strong central radio source Sgr A* and contributes to a gravitational well in which dark matter particles, such as the putative super-symmetric Neutralinos, could accumulate and annihilate into γ-rays.

Strong starburst activity has been recently identified in several regions of the central molecular zone (CMZ), for a total star formation rate (SFR) of $\approx 0.1\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (Yusef-Zadeh *et al.* 2005, Crocker *et al.* 2011b, Kendrew *et al.* 2012, Kendrew *et al.* 2013, Yusef-Zadeh *et al.* 2013), establishing a new connection between the GC and more distant, starburst galaxies, and allowing for the first time to study, in a nearby and well studied environment, the process of star formation. In total, the GC accounts for $\sim$ 10% of the formation of massive stars throughout the whole Galaxy (Figer *et al.* 2004). In some sense, the environment of the GC resembles that of the nucleus of starburst galaxies with large densities, large magnetic fields and possibly large-scale galactic winds advecting particles away from the center. The recent detection of the *so called* Fermi bubbles might be remnant of a much more intense burst of star formation that may have occurred a few million years ago (e.g. Lacki 2013).

2. Atmospheric Cherenkov technique

Very-high-energy γ-ray observations of the sky mainly relies on the atmospheric Cherenkov technique (ACT): very-high-energy particles entering the atmosphere interact with nuclei and produce a shower of ultra-relativistic particles. These particles, travelling faster than light in the atmosphere, emit Cherenkov light, resulting in a faint $\sim 2\,\mathrm{ns}$ flash that is detected on the ground by large ($> 100\,\mathrm{m}^2$) telescopes equipped with very fast cameras. Due to the spread of the Cherenkov light on the ground, imaging atmospheric Cherenkov telescopes (IACTs) can detect showers falling at distances larger than $100\,\mathrm{m}$ from the telescopes, resulting in effective areas of the order of $10^5\,\mathrm{m}^2$, even with modest size telescopes, and allowing to investigate the highest energy part of the cosmic accelerators where the fluxes are very low.

Stereoscopic observations of the same shower with several telescopes is used to provide a geometric reconstruction of the direction, impact point and energy of the primary particle, and detailed analysis of the light distribution in the camera allows one to discriminate the signal induced by γ-rays from the much more numerous hadronic cosmic rays.

Three major instruments are currently in operation in this field: MAGIC, consisting of two telescopes of $17\,\mathrm{m}$ diameter each and located on the Canary Islands; VERITAS, with four telescopes of $12\,\mathrm{m}$ diameter in the US, and H. E. S. S. in Namibia, comprising four telescopes of $14\,\mathrm{m}$ that was recently augmented with a fifth, giant $28\,\mathrm{m}$ diameter telescope that will allow the threshold of the array to be lowered down to $\sim 20\,\mathrm{GeV}$.

These instruments typically reach an angular resolution better than 0.1° for individual γ-rays with a energy resolution of $\sim 15\%$. Point source sensitivity at the level of $\sim 2 \times 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above $200\,\mathrm{GeV}$ is obtained in ~ 25 hours of observation at a mean observation zenith angle of 20° (e.g. Aharonian *et al.* 2006b, Albert *et al.* 2008, Holder *et al.* 2006). For a recent review on TeV astronomy, see Hinton & Hofmann (2010).

3. TeV observations of the Galactic center

3.1. *Central source*

3.1.1. *Energy spectrum and position*

At VHE a detection of the GC was first reported by the CANGAROO-II collaboration (Tsuchiya *et al.* 2004) but with a very steep spectrum $\underset{\cdot}{\mathrm{N}}/\underset{\cdot}{\mathrm{E}} \propto E^{-4.6\pm0.5}$ that was subsequently contradicted by detailed measurements from the H. E. S. S. collaboration. After a marginal detection from the Whipple collaboration (Kosack *et al.* 2004), TeV emission was finally confirmed and firmly established by the H. E. S. S. collaboration with very high statistical significance (Aharonian *et al.* 2004) and by the MAGIC telescope (Albert *et al.* 2006).

The energy spectrum derived by the H. E. S. S. collaboration from nearly 100 hours of data collected between 2004 and 2006 (Aharonian *et al.* 2009) is well described by a hard power law with a high energy exponential cut-off:

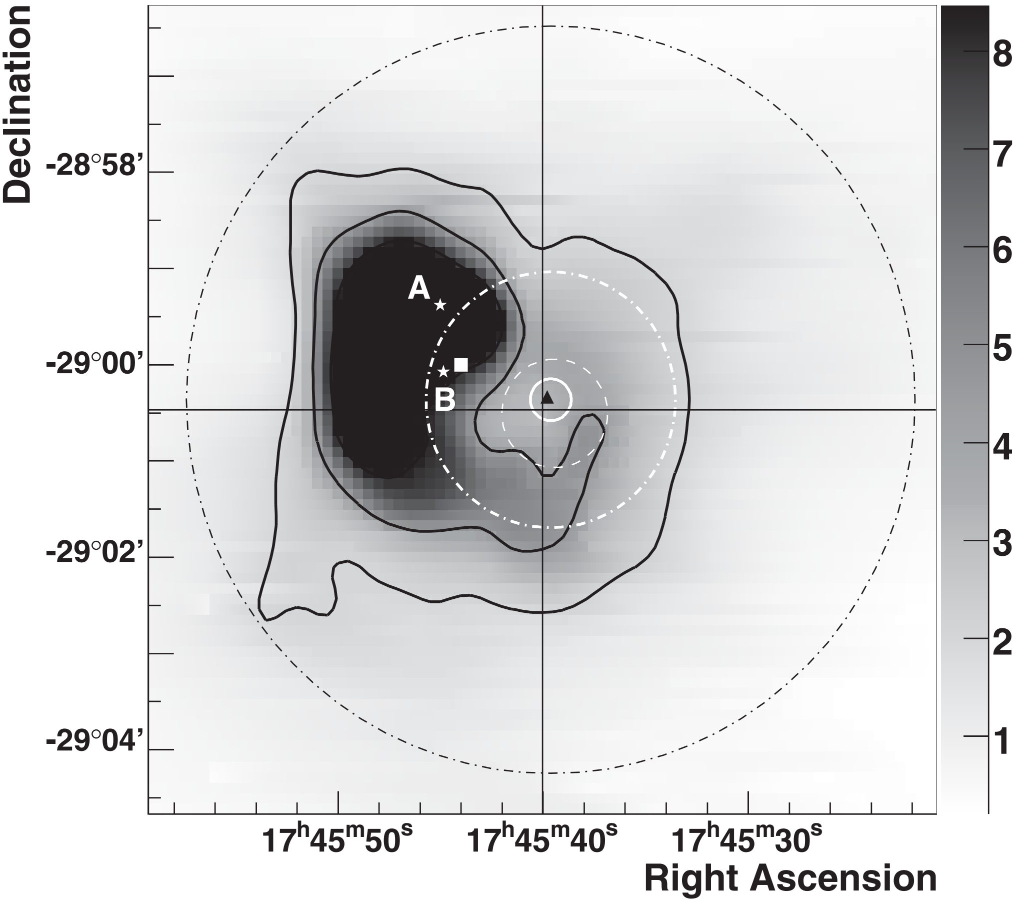

Figure 1. 90 cm VLA radio flux map density (LaRosa *et al.* 2000) of the innermost 20 pc of the GC, showing emission from the SNR Sgr A East. Reproduced from Aharonian *et al.* (2006). The centroid position of the VHE emission (white circle, 68% CL) is fully consistent with the position of Sgr A* (cross hair, Reid *et al.* 1999) and the head position of G359.95-0.04 (black triangle, Wang *et al.* 2006). See Aharonian *et al.* (2006) for a complete description of the figure.

$$\begin{aligned}
\frac{\underset{\cdot}{\mathrm{N}}}{\underset{\cdot}{\mathrm{E}}} &= \Phi_0 \left(\frac{E}{1\mathrm{TeV}}\right)^{-\Gamma} \times \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right) \\
\Phi_0 &= (2.55 \pm 0.06_{\mathrm{stat}} \pm 0.40_{\mathrm{syst}}) \times 10^{-12}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \\
\Gamma &= 2.10 \pm 0.04_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}} \\
E_{\mathrm{cut}} &= (15.7 \pm 3.4_{\mathrm{stat}} \pm 2.5_{\mathrm{syst}})\,\mathrm{TeV}
\end{aligned}$$

The contamination of this spectrum by the underlying diffuse emission (see next section) is estimated to be 13% ± 1% integrated over the energy range. The VHE emission is point-like (extension $< 1.2'$ RMS), with a centroid position located $7'' \pm 14''_{\mathrm{stat}} \pm 28''_{\mathrm{sys}}$ from Sgr A*. Within this region, the most promising candidates for the TeV emission are the immediate vicinity of the black hole, the radio-bright, shell-like supernova remnant Sgr A East (e.g. Crocker *et al.* 2005) and the pulsar wind nebula (PWN) candidate G359.94−20.04 (Wang *et al.* 2006).

After a careful investigation of the pointing systematics of the H. E. S. S. telescopes, and using astrometric pointing corrections, the systematic error on the centroid

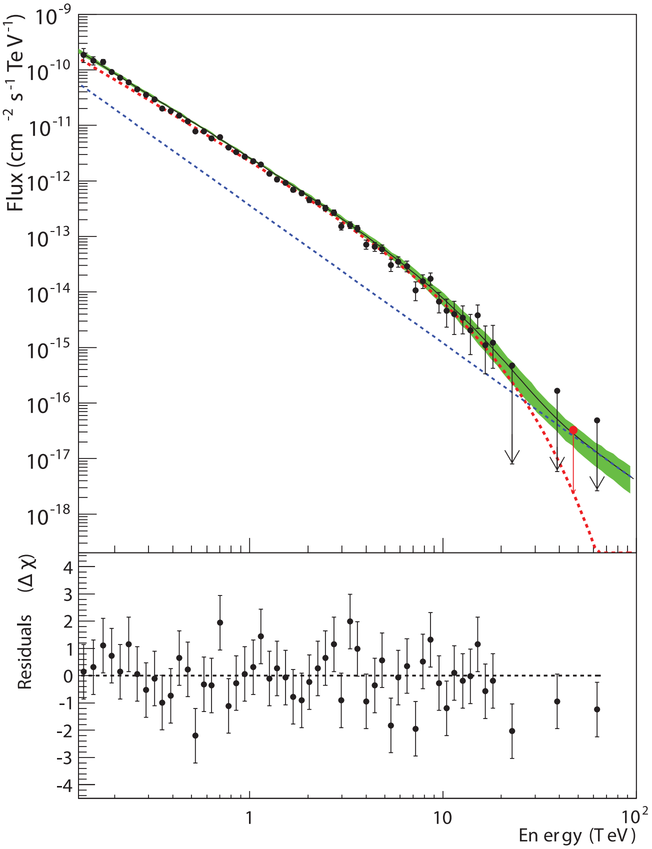

Figure 2. Intrinsic VHE energy spectrum of Sgr A*. Reproduced from Vianna *et al.* (2013) The blue line corresponds to the contribution of the diffuse emission, and the red one is the intrinsic contribution of the central, point-like source. [A COLOR VERSION IS AVAILABLE ONLINE.]

position of the TeV emission was reduced to 13″ on a subset of data (Acero *et al.* 2010), thus allowing the regions of intense emission from Sgr A East to be excluded as main contributors to the VHE emission (see Figure 1).

Recently, H. E. S. S. published an updated VHE spectrum of Sgr A* (Viana *et al.* 2013) using a twice larger data set of 220 h of observation spanning the years from 2004 to 2012 and taking into account the contamination by the diffuse emission. The intrinsic spectrum of Sgr A* is marginally harder than previous measurements ($\Gamma = 2.04 \pm 0.03_{\rm stat} \pm 0.10_{\rm syst}$) with a cut-off at significantly lower energy ($E_{\rm cut} = 7.9 \pm 1.3_{\rm stat} \pm 1.2_{\rm syst}$ TeV), whose implications are yet to be investigated in detail. In particular, γ-rays from the diffuse emission dominate over the point-like source at energies above ~ 25 TeV.

Due to its declination, Sgr A* can only be observed by VERITAS and MAGIC at large zenith angles ($\theta = 60 - 66^\circ$) resulting in a high energy threshold $E_{\rm th} \approx 2.5$ TeV and a degraded angular resolution, partially compensated for by a larger effective area. Results of VERITAS observations between 2010 and 2012 were reported by Beilicke *et al.* (2012) on a data-set of 46 hours of observations, resulting in an energy spectrum compatible, at a first glance, with that measured by H. E. S. S.. Detailed studies of the possible systematic effects induced by large zenith angle observations are being carried out and further observations should help to constrain the high energy cutoff.

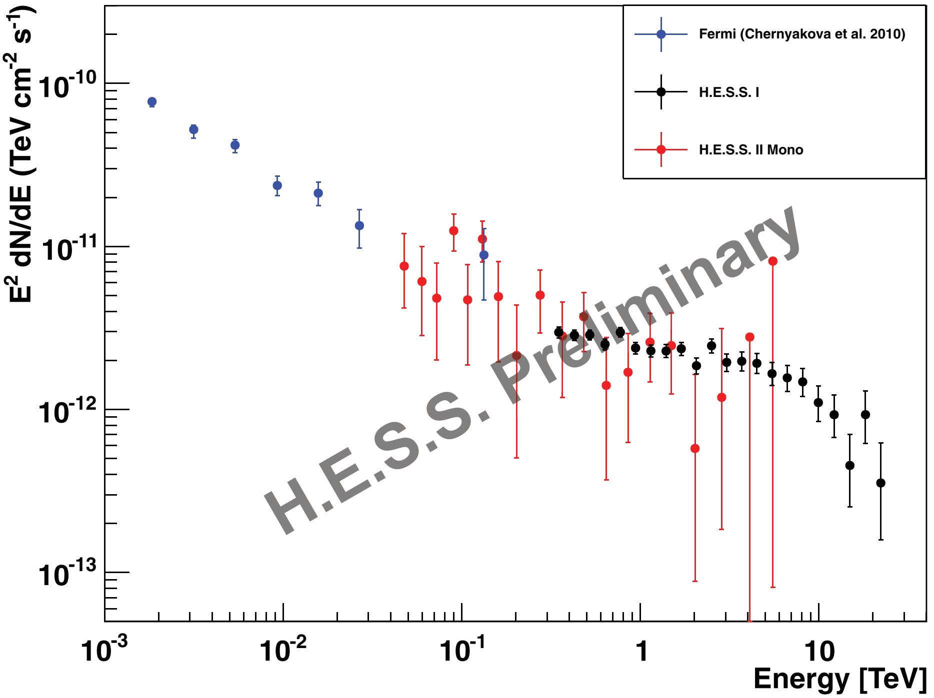

Figure 3. Preliminary spectrum of Sgr A* obtained with HESS-II commissioning data. [A COLOR VERSION IS AVAILABLE ONLINE.]

At lower energies, between the existing IACTs and the *Fermi* space telescope, the H. E. S. S.-II telescope recently began operations, aiming to cover the $\lesssim 100$ GeV energy range with unprecedented sensitivity. A preliminary energy spectrum of Sgr A* obtained with commissioning data is shown on Figure 3 compared with the published H. E. S. S. and *Fermi*/LAT spectrum, and confirms that low energy capabilities of this new instrument will be ideally suited for, among other, the investigation of the putative 130 GeV *Fermi* line (Bringmann *et al.* 2012, Weniger 2012).

3.1.2. *Variability*

Besides the pure positional association, which is limited by the angular resolution of IACTs, time variability might provide the strongest constraint allowing to pin-point the origin of the VHE emission. Indeed, despite the low level of continuum X-ray emission (Baganoff *et al.* 2001), bright and frequent flares of Sgr A* were detected in several bands, such as X-rays and IR, thus providing strong evidence that the X-ray emission is related to accretion onto the supermassive black hole (SMBH) at the Galactic centre. Flare durations as short as a few minutes limit the emission region to within < 10 Schwarzschild radii of the black hole.

Quasi-periodic oscillations of periods of $\sim$ 100 s, 219 s, 700 s, 1150 s and 2250 s have been observed in data collected with the *Chandra* and *XMM-Newton* observatories in 2000 and 2002 (Aschenbach *et al.* 2004) but have not been confirmed at other wavelengths.

Despite extensive searches over several years, no hint for variability has been found in the VHE data (Aharonian *et al.* 2009, Beilicke *et al.* 2012), neither in flux level nor in spectral shape. Simultaneous observations of Sgr A* by H. E. S. S. and *Chandra* were performed during 2005 July/August. During this period, two significant X-ray flares where detected by *Chandra*, one of which has simultaneous H. E. S. S. coverage (Aharonian *et al.* 2008) and corresponded to an increase of the X-ray flux by a factor of 9. The absence of a significant increase in the $> 160\,\mathrm{GeV}$ γ-ray flux from Sgr A* during this event is a rather strong indication that the keV and TeV emission cannot be attributed to the same parent population of particles and might even originate from different objects in the sky. A coordinated XVP (X-ray Visionary Projects) observation program of Sgr A* is currently under way with a total of 18 instruments in the program to further investigate this issue. Simultaneous coverage of three X-ray flares has been obtained, and results were presented at this conference (Kosack *et al.* 2013).

3.1.3. *Interpretation*

Given the complexity of the GC region, many objects could contribute to the observed TeV emission.

Almost immediately after the discovery of the TeV emission, the central black hole was proposed (Aharonian & Neronov 2005) as the source of the emission in a model were protons are accelerated close to the event horizon of the SMBH diffuse out into the interstellar medium, and produce γ-rays through the decay of neutral pions. The intensity of the emission would depend on the history of particle injection and diffusion over time scales of $\sim 10^5$ yr.

Following this idea, Chernyakova *et al.* (2010) proposed a detailed model based on energy-dependent diffusion of protons accelerated in the BH vicinity (a few tens of Schwarzschild radii). At the highest energies ($> 10\,\mathrm{TeV}$), ballistic propagation would result in a γ-ray flux that reflects the underlying source spectrum. Variability at time scales of $\sim 10\,\mathrm{yr}$ would be expected, reflecting the variation of the accretion flow onto the black hole. At the lowest energies ($< 1\,\mathrm{GeV}$), efficient trapping of CR would result in an intensified γ-ray emission with, again, a spectral shape reflecting the source spectrum. In that regime, particle diffusion in the central region would proceed much slower compared to the diffusion in the Galactic Disk. Variability at timescales of $\sim 10^4$ yr is predicted in this energy range, corresponding to old flares. The intermediate energy regime would be characterized by a steeper spectrum shape caused by the energy dependency of the diffusion coefficient. The prediction of this model, shown in Figure 4, are consistent with the measurement of *Fermi*/LAT and H. E. S. S.. An extension of the signal of the order of $50''$ is expected, which is beyond the capabilities of current instruments to detect.

Atoyan & Dermer (2004) proposed a model based on a *black hole plerion* in which electrons are accelerated at the termination shock of a leptonic wind and subsequently produce γ-rays by inverse Compton scattering. This model reproduces the IR and X-ray flaring, and predicts a variability at time scales of $\sim 100\,\mathrm{yr}$ at TeV energies. This leptonic model underestimates the GeV emission flux by almost two orders of magnitude (due to the intrinsic shape of inverse Compton radiation) and would require the GeV emission to be attributed to another object and/or mechanism. Liu *et al.* (2006) proposed a derived model in which protons would be accelerated in the wind-shocked medium surrounding the black hole (up to $\sim 10^{37}\,\mathrm{erg\,s^{-1}}$), would interact with the ISM and produce a γ-ray emission that would reproduce the TeV observations.

Similarly, after the discovery of the PWN candidate G359.94$-$20.04 (Wang *et al.* 2006), leptonic models were proposed (Hinton & Aharonian 2007) that properly reproduce the TeV data but suffer from the same problem of underestimation of the GeV emission that appears to be quite generic of leptonic models. In addition, all leptonic models are subject to the very fast cooling rates of electrons caused by the intense photon fields and magnetic fields in the central part of the Galaxy.

A PWN model would in general imply a constant TeV flux as the evolution time scale of PWNs is in the range $100 - 1000\,\mathrm{yr}$.

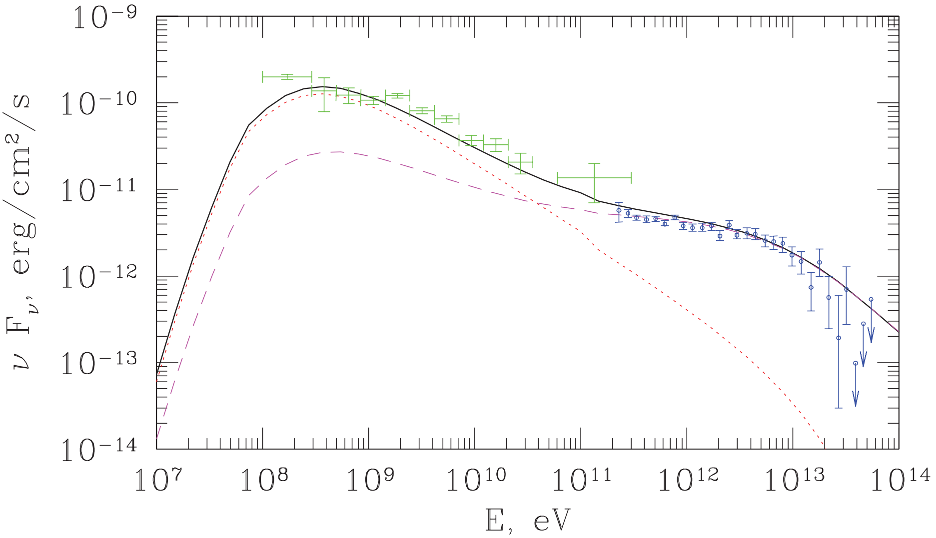

Figure 4. Combined *Fermi* (green points) and H. E. S. S. (blue points) explained by superposition (black solid line) of a proton flare of 10 years duration that happened 300 years ago (magenta dashed line) and a constant source that switched on 10^4 years ago (red dotted line). Reproduced from Chernyakova (2010). [A COLOR VERSION IS AVAILABLE ONLINE.]

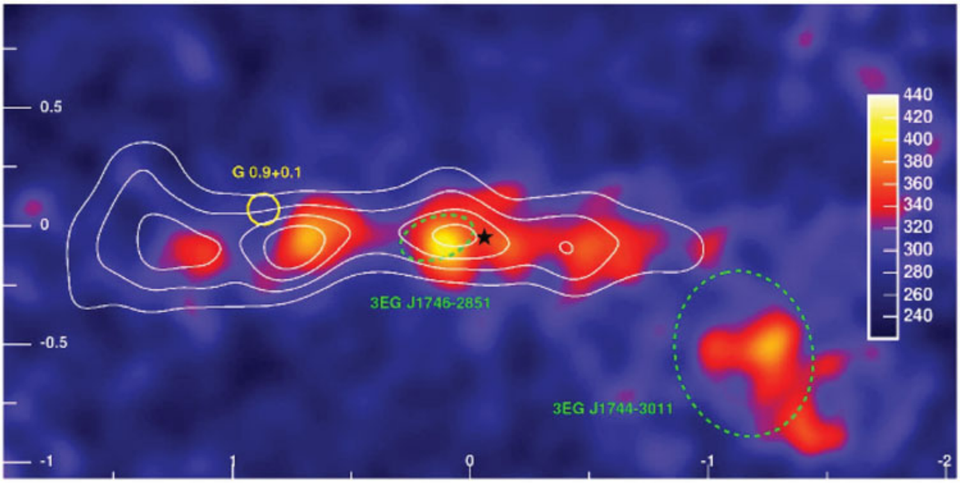

Figure 5. Diffuse emission. Reproduced from Aharonian *et al.* (2006a).
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3.2. *Diffuse emission*

3.2.1. *Observation*

Diffuse TeV emission across the Galactic center ridge was first detected by the H. E. S. S. experiment (Aharonian *et al.* 2006a). The corresponding γ-ray sky map, after subtraction of two bright point sources, is shown in Figure 5. The γ-ray emission is correlated with the complex of giant molecular clouds in the central 200 pc of the Milky Way, showing peaks at the position of the densest parts of the CMZ, Sgr B, C, etc. This correlation is expected in the case of hadronic production mechanisms, such as the interaction of

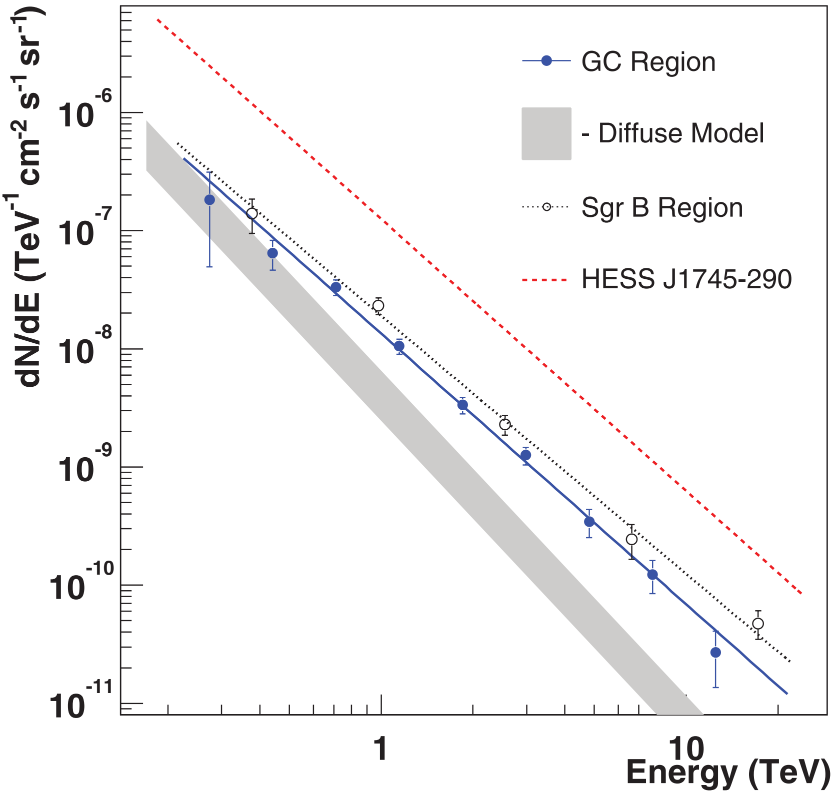

Figure 6. Spectrum of diffuse emission compared to expectation from a propagation model. Reproduced from Aharonian *et al.* (2006a). [A COLOR VERSION IS AVAILABLE ONLINE.]

cosmic rays with the interstellar medium. Interestingly enough, the correlation between TeV emission and molecular gas breaks at $l = 1.3°$ where no significant emission is detected despite the presence of a very massive cloud (Figure 5).

The spectrum of the diffuse emission, shown in Figure 6, is harder ($\Gamma = 2.29 \pm 0.07_{\rm stat} \pm 0.20_{\rm sys}$) than the prediction from a diffuse model (grey band on the figure) assuming a cosmic-ray spectrum similar to that of the Earth neighbourhood, and resembles the spectrum that can naturally emerge from a *Fermi* diffusive acceleration. The measured γ-ray flux (> 1 TeV), which is in excess to the prediction of this model, implies a high-energy cosmic ray density $4 - 10$ times larger than its value in the solar system, thus pointing towards neighbouring accelerators.

3.2.2. *Discussion*

The remarkable similarity between the spectrum of the diffuse emission and that of the central point source immediately pointed toward the SMBH being at the origin of both emissions. In Aharonian *et al.* (2006a), it was proposed that a single eruptive event (SN explosion or flare from Sgr A*) releasing $\sim 10^{51}$ erg could account for the observed emission given a reasonable conversion efficiency into CR of $\sim 10\%$. The diffusion time to a distance of 1° from the GC was estimated to about 10 kyr (with, however, large uncertaintines) and the lack of correlation at $l = 1.3°$ would just reflect the propagation time being larger than the age of the SN explosion. This single eruptive event could plausibly be associated with the central SMBH.

Despite this large-scale non-thermal emission, the GC is significantly underluminous (e.g. Crocker 2011) in both radio continuum and TeV, given the amount of star formation occuring in the neighbourhood. The favoured explanation for this low non-thermal luminosity is that cosmic rays produced in the SN shells are removed from the CMZ by advection on a powerful GC wind (Crocker 2011) of speed $400 - 1200\,\mathrm{km\,s^{-1}}$, revealed by the radio continum emission and giving rise to the Fermi bubbles (e.g. Lacki 2013). In that case particles would be removed from the GC predominantly by advection rather than by diffusion, cosmic rays would not be able to penetrate into the cores of the region's dense molecular clouds (Crocker *et al.* 2011b) and the diffuse emission no longer easily be explained by a single event at the GC.

Yusef-Zadeh *et al.* (2007) proposed a model based on *in situ* acceleration of cosmic rays in molecular clouds (Sgr C, Sgr B1 and Sgr B2), in which a large fraction of the TeV diffuse emission would be due to inverse-Compton radiation of relativistic electrons. The required energy in cosmic rays is then estimated from the non-thermal radio continuum.

Wommer *et al.* (2008), using a Monte Carlo approach, simulated the diffusion of protons in a turbulent magnetic field by solving the individual proton trajectories. They find that the diffusion is too slow to account for $p - p$ scattering more than a fraction of a degree away from the central source and conclude that it is very unlikely that relativistic protons accelerated by Sgr A* could fill the $\sim 2^\circ$ region surrounding the black hole and give rise to the observed TeV emission. Their simulations indicate that, if TeV photons are produced in hadronic interactions with the ISM, the relativistic protons must be accelerated *in situ*, throughout the intercloud medium, and are not injected into the ISM by individual objects. More recently, Crocker *et al.* (2011b) proposed a steady-state, single zone diffuse model that provides an acceptable fit to the H. E. S. S. data.

4. Starburst galaxies

4.1. *Introduction*

Starburst galaxies are characterized by intense star formation in a very localized region, called the *starburst region*. This enhanced stellar formation activity is believed to be triggered either by galaxy mergers or by galactic bar instabilities and can last a few millions years. In both cases, the starburst activity results from a disturbance of the interstellar gas equilibrium. The starburst regions exhibit very high gas density ($\sim 100\times$ that of normal galaxies), and consequently high star formation as well as a strongly increased supernova (SN) explosion rate. For these reasons, starburst galaxies were identified very early as potential γ-ray emitters with cosmic ray densities expected to be two orders of magnitude larger than in the Milky Way (e.g. Völk *et al.* 1989, Akyuz *et al.* 1991, Paglione *et al.* 1996).

M 82 and NGC 253 were identified very early as the most promising candidates, because of their proximity ($D \approx 2.5 - 4$ Mpc), their very dense ISM, and intense star-formation activity. The dominant γ-ray production channel is thought to be hadronic, through the production and subsequent decay of π^0. The γ-ray luminosity, however, not only depends on the CR density, but also on their conversion efficiency into γ-rays, which involves the ratio between the escape and pion-production timescales. The fraction of cosmic rays channeled into γ-ray production is often referred to as *calorimetric fraction*. In addition to the inelastic $(p - p)$ interactions, cosmic rays can be removed from the starburst region either by diffusion or by advection on the strong starburst wind (referred to as *superwind*).

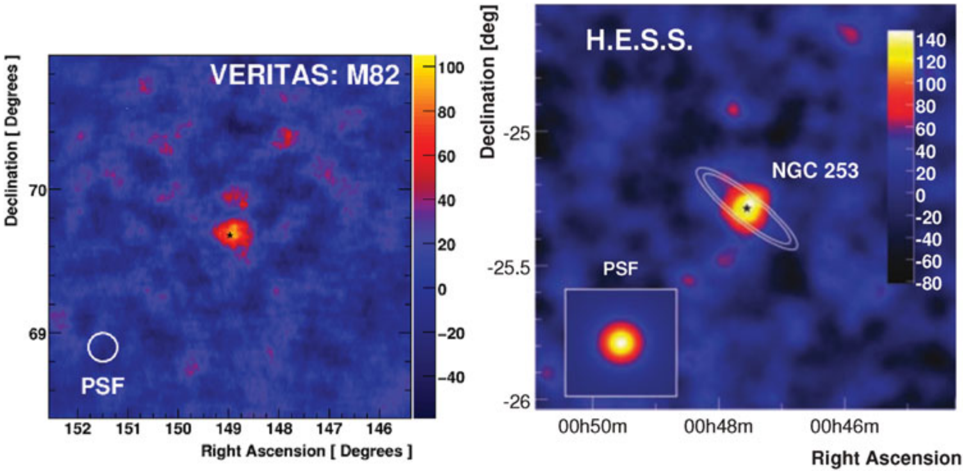

Figure 7. Left: VERITAS γ-ray map of M 82. Reproduced from Acciari *et al.* (2009). **Right:** H. E. S. S. γ-ray map of NGC 253. White contours depict the optical emission from the whole galaxy with contours of constant surface brightness. From Acero *et al.* (2009). [A COLOR VERSION IS AVAILABLE ONLINE.]

Because of energy losses in large gas densities, the interaction time of cosmic rays in starburst galaxies is thought to be of the order of 1 Myr, a factor of ~ 30 shorter than in the Milky Way. To be maintained at this level, the population of cosmic rays needs a correspondingly larger energy input, most likely provided by the larger supernova rate. Detailed comparison between cosmic ray populations in starburst galaxies and in normal galaxies might provide a new insight on cosmic ray production mechanisms.

4.2. *TeV observations: M 82 and NGC 253*

After many years of unfruitful search, M 82 & NGC 253 have been detected both at GeV (Abdo *et al.* 2010) and at TeV energies (Acciari *et al.* 2009, Acero *et al.* 2009, Abramowski *et al.* 2012) after very long exposures of 100 to 200 h, at the limit of the capabilities of modern instruments. Both sources appear point-like at the resolution of IACTs (Figure 7), and very faint ($< 1\%$ of the Crab Nebula). Both of them exhibit an intense star-forming region of about ~ 200 pc, similar to the size of the CMZ in the Milky Way.

The energy spectrum of NGC 253 is shown in Figure 8 and can be fitted by a pure power law from 200 MeV to 10 TeV. The absence of any spectral break and the rather hard spectral index (close to the assumed particle source index $s \approx 2.3$) strongly suggest that cosmic rays are removed from the starburst region in an energy-independent way, i.e. that advection dominates over diffusion, which seems reasonable for wind speeds of the order of several hundred km s^{-1}. Indeed, the equilibrium CR proton spectrum is roughly $N(E) \approx Q(E) \times \tau(E)$ in a simple one-zone model, where $Q(E) \propto E^{-p}$ is the injection spectrum and $\tau(E)$ the proton lifetime including escape and inelastic pion losses. The advection time and pionic lifetime are almost energy independent, so the equilibrium spectrum reflects the source spectrum.

Due to the large ISM densities, the production of γ-rays is expected to occur mainly through hadronic process (inelastic $p{-}p$ collisions), except perhaps at the highest energies (due to a harder inverse Compton emission spectrum). In the case of M 82, observation of

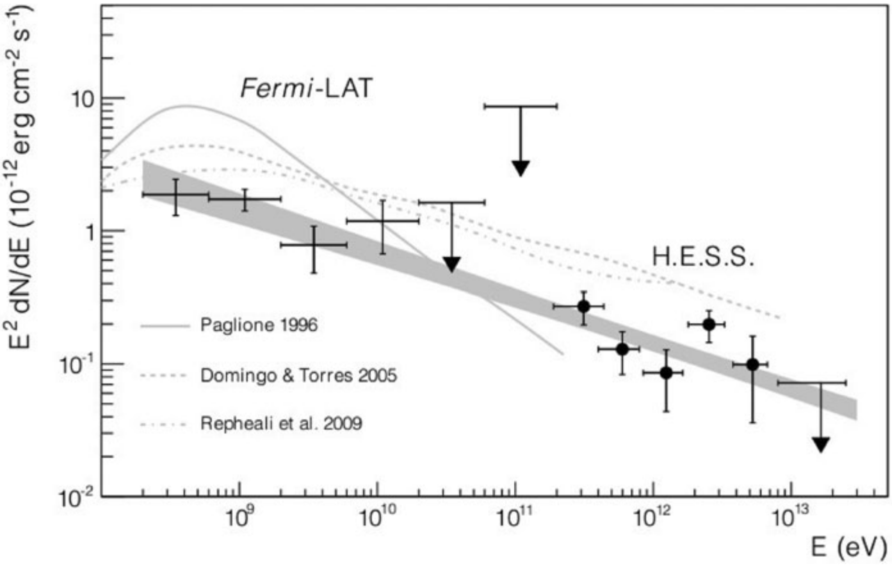

Figure 8. Energy spectrum of NGC 253. Reproduced from Abramowski *et al.* (2012).

synchrotron radio emission sets a limit on the population of cosmic ray electrons under an assumption on the strength of the magnetic field of the order of $80\,\mu$G (Karlsson 2009), and also points towards dominant hadronic channels for the production of VHE γ-rays.

For a reasonable set of parameters, and 10% efficiency for CR acceleration in starburst SN remnants, the calorimetric fraction of NGC 253 is estimated to be $20 - 30\%$ with, however, rather large uncertainties.

The HE and VHE γ-ray energy spectrum of M 82 looks similar, within large statistical uncertainties, to that of NGC 253. With a detailed modeling, Lacki *et al.* (2011) obtain a calorimetric fraction of 40% and 20% respectively for M 82 and NGC 253, consistent with the previous findings. In the Milky Way, the calorimetric fraction does not exceed 10% based on grammage estimates and diffusion models. In general, the GeV/TeV flux of galaxies increases with the star formation rate (as estimated from the far infra-red luminosity) and with the gas density. At low densities, protons escape easily and the γ-ray emission is weak. As the density increases, the calorimetric fraction increases as well, resulting in larger γ-ray emission. This relation is used by Lacki *et al.* (2011) to predict the detectability of nearby starburst galaxies by existing and upcoming IACTs, such as the Cherenkov Telescope Array (CTA).

The TeV luminosities ($E > 100\,\mathrm{GeV}$) of NGC 253 and M 82 are $\sim 2 \times 10^{38}$erg s^{-1} and $\sim 2 \times 10^{39}$erg s^{-1} respectively, well above the luminosity of the Galactic center region ($\sim 10^{35}$erg s^{-1}). The starburst region therefore completely outshines the diffuse emission of the complete galaxy.

5. Conclusion

A strong connection between the central region of our own Galaxy and starburst galaxies has emerged in the last ten years, in particular with the observation of large-scale winds attributed to the intense starburst activity occuring in the CMZ and possibly

	NGC 253	M 82	CMZ
Distance	$2.6-3.5\,\mathrm{Mpc}$	$3.4\,\mathrm{Mpc}$	$8.5\,\mathrm{kpc}$
SFR Rate	$\approx 5\mathrm{M}_\odot\,\mathrm{yr}^{-1}$	$\approx 10\mathrm{M}_\odot\,\mathrm{yr}^{-1}$	$\approx 0.02\mathrm{M}_\odot\,\mathrm{yr}^{-1}$
SNR Rate	$\approx 0.03\,\mathrm{yr}^{-1}$	$\approx 0.1\,\mathrm{yr}^{-1}$	$\approx 4\times10^{-4}\,\mathrm{yr}^{-1}$
CR Density	$\sim 100\,\mathrm{eV\,cm}^{-3}$	$\sim 250\,\mathrm{eV\,cm}^{-3}$	$\sim 4\,\mathrm{eV\,cm}^{-3}$
Gas Density	$580\,\mathrm{cm}^{-3}$	$150\,\mathrm{cm}^{-3}$	$\sim 100\,\mathrm{cm}^{-3}$
TeV luminosity	$\sim 2\times10^{38}\mathrm{erg\ s}^{-1}$	$\sim 2\times10^{39}\mathrm{erg\ s}^{-1}$	$\sim 10^{35}\mathrm{erg\ s}^{-1}$
Spectral Index Γ	$2.14\pm0.18_{\mathrm{stat}}\pm0.30_{\mathrm{sys}}$	$2.5\pm0.6_{\mathrm{stat}}\pm0.2_{\mathrm{sys}}$	$2.29\pm0.07_{\mathrm{stat}}\pm0.20_{\mathrm{sys}}$
Calorimetric Fraction	$20-30\%$	$\sim 40\%$	$\sim 1\%$

Table 1. Parameters of TeV starburst galaxies compared to the central molecular zone of the Milky Way (Dalcanton *et al.* 2009, Engelbracht *et al.* 1998, Sakai *et al.* 1999, Melo *et al.* 2002, Förster Schreiber *et al.* 2003, Lacki *et al.* 2011, Ferrière *et al.* 2007).

giving rise to the so called Fermi bubbles. Diffuse TeV emission across the Galactic center ridge, observed by H. E. S. S., could result from the past activity of the central black hole Sgr A*, but may also be attributed to cosmic-ray acceleration in the dense, star-forming molecular clouds observed in the CMZ. In this context, a comparison between the properties of the CMZ and the known, TeV-emitting, starburst galaxies is presented in Table 1.

Despite roughly comparable gas densities, the CMZ appears very significantly underluminous compared to starburst galaxies. The factor of 10^3-10^4 in TeV luminosity could result partially from lower CR densities (induced by a smaller supernova rate in the CMZ) and an efficient removal of particles from the CMZ by advection in the superwind. This would result in a significantly lower calorimetric fraction compared to starburst galaxies.

Many years after having been predicted as γ-ray emitters, starburst galaxies were firmly established as a new TeV source class only recently by deep H. E. S. S. and VERITAS observations. Their emission level, consistent with early predictions, is at the limit of the capabilities of the current generation of instruments and indicates that about $20-40\%$ of the accelerated cosmic rays are channeled into γ-ray production though hadronic interaction in the ISM.

The TeV source observed at the center of the Galaxy is spatially coincident with the SMBH Sgr A* and does not show any variability in this energy domain so far, in strong contrast with other wavelength such as IR and X-rays. Its emission could arise from protons accelerated in the immediate vicinity of the black hole, but alternate mechanisms or sources cannot be excluded, in particular due to the relatively limited resolution of the current instruments. Long-term monitoring is needed to check whether variability is present at time scales of $\sim 10\,\mathrm{yr}$ as predicted by several models, and to study in detail the high energy cut-off of the TeV emission.

Further deep observations with the existing and upcoming generation of IACTs will be needed to further investigate the connection between the GC and starburst galaxies. In this regard, the improved sensitivity and superior angular resolution of CTA will very likely greatly improve our knowledge on this fascinating region.

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