The H.E.S.S. View of the Galactic Centre

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Abstract

We present an overview of the H.E.S.S. observations of the Galactic Centre region, in comparison with those of other instruments, and briefly discuss the astrophysical implications of the reported results.

1 Introduction

The central 100 pc of our Galaxy is an extraordinary region that harbours many remarkable objects - potential sites of effective particle acceleration and copious γ-ray production. The wide field of view of the High Energy Stereoscopic System (H.E.S.S.) of imaging atmospheric Cherenkov telescopes, (5°), allows us to observe all of these candidate sources with a single pointing of the instrument.

Perhaps the most exciting of these candidates is the mysterious source Sgr A* at the kinematic centre of our galaxy. This source has now been identified as a supermassive (2.6×10^6 M$_\odot$) black hole (see e.g. [1]). Variable (non-thermal) X-ray and infrared emission from this source confirm its very compact nature. Several mechanisms for production of high energy γ-ray emission close to the event horizon of massive black holes have been suggested. These include interactions of ultra-high energy protons with the magnetic and radiation fields, as well as with the gas of the accretion flow, and curvature and inverse Compton radiation of multi-TeV electrons.

Very close to Sgr A* lies the unusually compact and powerfully supernova remnant (SNR) Sgr A East. As the prime candidate for the acceleration of cosmic rays, SNRs have long been of interest to γ-ray astronomers. The very dense medium in and around this remnant provides an enhanced target density for the production of γ-rays produced in interactions of particles accelerated in the supernova shell. This region also contains several other SNRs and pulsar wind nebulae such as G 0.9+0.1 and the so-called Mouse. Diffuse TeV emission is also expected from interactions of cosmic rays with dense molecular clouds within the central 100 pc region.

Yet another tantalizing possibility is the detection of dark matter annihilation in the central cusp in the dark matter density profile of our galaxy.

VHE γ-ray observations of this region by the H.E.S.S., CANGAROO and Whipple collaborations were published in 2004. Below we overview the HESS observations and compare our results with the results reported by the CANGAROO and Whipple groups.

2 Very high energy γ-ray observations

The H.E.S.S. array, in the Khomas Highlands of Namibia, is the first 3rd generation instrument [2] to be completed and reaches a sensitivity one order of magnitude below the 2nd generation instruments. For comparison the TeV energy flux at the level of 0.1 Crab from a point-like source can be probed by HESS in less than 30 minutes of observation time, while the detection of the same flux by the previous generation detectors required tens of hours of observations.

H.E.S.S. consists of four 13 m diameter telescopes operating in a stereoscopic coincidence mode [3]. The greatly increased mirror area of the system results in a reduced energy threshold of ≈100 GeV and the stereoscopic measurement of showers results in improved energy and angular resolution. The wide field of view of the instrument ≈5° also provides an advantage in observations of extended objects or complex regions.

The first VHE observations of the GC region were conducted by the Whipple collaboration between 1995 and 2003. These observations occurred at large zenith angles, due to the Northern Hemisphere location of the instrument, resulting in an energy threshold of 2.8 TeV, and resulted in a marginal detection with a significance of 3.7 σ from 26 hours of data [4]. The position of the γ-ray excess is consistent with the position of Sgr A* within the $15'$ 95% C.L. error circle. The flux of this GC source has recently been revised downwards by $\sim$40% to $\approx 5 \times 10^{-13}$ cm^{-2}s^{-1} (above 2.8 TeV) [5].

Observations with the CANGAROO-II instrument in 2001 and 2002 led to the detection of sub-TeV γ-rays with an origin within $6'$ of Sgr A* from 67 hours of (on-source) data [6]. The reported spectrum is very steep, $F(E) \propto E^{-4.6\pm0.5}$ and incompatible with the Whipple observation. However, a recent reanalysis of these data yielded a much larger error on the photon index: $-4.6^{+1.2}_{-5.0}$ [7].

The first H.E.S.S. data on the GC region were taken during the construction phase of the instrument. This 2003 (17 hour) dataset revealed a clear VHE γ-ray signal from the Galactic Centre (Fig. 1) [8]. Using the improved sensitivity and angular resolution of H.E.S.S. this γ-ray signal could be localised to within $1'$ and is still compatible with the position of Sgr A*. Although the localisation of the γ-ray emission with H.E.S.S. is almost a factor 10 better than previous measurements, an unambiguous identification of the source is still not possible given the complex nature of the GC region. We therefore refer to this source as HESS J1745$-$290. The energy spectrum of the source is consistent with a power law with photon index $\Gamma = 2.21 \pm 0.09$ and a flux normalisation at 1 TeV of $F_0 = (2.50 \pm 0.21) \times 10^{-12}$cm^{-2}s^{-1}TeV^{-1}. Figure 2 shows a comparison of the energy spectrum of the GC sources as measured by H.E.S.S. and Whipple. The large systematic error on the CANGAROO-II result makes a visual representation of these data difficult, they are therefore omitted from this figure. However, we note that even with the increased systematic error, the CANGAROO-II and H.E.S.S. photon indices differ at the $\approx 2\sigma$ level.

A 50 hour observation with the full 4-telescope array in 2004 greatly increased the statistical significance of the signal from HESS J1745$-$290. (up to 36 σ). A preliminary spectral analysis yields a result consistent with the 2003 data but with extended energy coverage. The error on the position of the γ-ray excess is now dominated by systematic errors of approximately $20''$ in each coordinate. Therefore, whilst the position of the γ-ray signal seen by H.E.S.S. is consistent with the position of Sgr A* an origin of the emission in the supernova remnant Sgr A East cannot be excluded at 95% confidence. It is anticipated that the systematic error on the position of HESS J1745$-$290 can be reduced to $\sim 10''$ during 2005. A significance map from H.E.S.S. 2004 data is shown in the lower panel of Fig. 1. As well as the strong signal from HESS J1745$-$290 a second source is clearly visible $\sim$1° away from Sgr A. This new source has been identified as the SNR G 0.9+0.1 [9].

2.1 The Supernova Remnant G 0.9+0.1

The supernova remnant G 0.9+0.1 is a composite object, consisting of a bright compact core ($\sim 2^\circ$ across) surrounded by an $8'$ diameter shell [10]. X-ray observations of the nebula [11][12] showed that the core region is very likely a pulsar wind nebula (PWN). These X-ray observations imply the existence of a population of very energetic electrons (> 10 TeV) in the core of the remnant. VHE γ-ray emission from this object was detected serendipitously by H.E.S.S. during observations of the GC in 2004. The observed energy spectrum is consistent with a power law with photon index $\Gamma = 2.40 \pm 0.11_{stat} \pm 0.20_{sys}$ and a flux above 200 GeV of $(5.7 \pm 0.7_{stat} \pm 1.2_{sys}) \times 10^{-12}$ cm^{-2}s^{-1}. As can be seen from Figure 3, the detected γ-ray source is consistent with the point-spread function of the instrument, allowing us to derive upper limits on the size of the emission region, assuming a Gaussian-like ($\sigma_{\rm source} < 1.3'$) or a shell-like ($r_{\rm source} < 2.2'$) morphology. VHE emission from the SNR shell therefore appears to be excluded and an origin in the plerionic core of the nebula seems likely. A plausible interpretation of the emission is Inverse Compton radiation off the energetic electrons in the PWN on the enhanced radiation fields of the GC region.

Although G 0.9+0.1 is one of the weakest sources ever detected at TeV energies, the detection presented here is statistically highly significant ($13\,\sigma$), demonstrating the sensitivity of the H.E.S.S. instrument.

3 On the origin of TeV emission

The origin of TeV radiation detected by H.E.S.S. from the direction of the Galactic Centre is not yet established. The 3-arcminute upper limit on the source size implies that several objects, in particular the young SNR Sgr A East [14], the Dark Matter Halo [15], the compact radio source Sgr A* (with several γ-ray production scenarios with both direct and indirect links to the central massive black hole [16, 17]) can be considered as potential candidates for TeV emission within the central 10 pc region.

In addition to γ-rays emitted in compact regions in the vicinity of the massive black hole, one should expect also a diffuse (extended) component of radiation associated with interactions of the runaway protons with the surrounding dense interstellar gas[18]. The relative contribution of this component to the total TeV flux, as well as the spectral and angular characteristics of π^0-decay γ-rays significantly depend on the rate of injection of accelerated protons into the interstellar medium, as well as on the regime of (energy-dependent) diffusion of protons in the dense central region. For certain combinations of principal model parameters the diffuse γ-rays from pp interactions can satisfactorily explain both the absolute flux and energy spectrum of TeV radiation reported by H.E.S.S.. This is demonstrated in Fig.4

The flux of this radiation component depends not only on the density of the ambient gas and the injection rate of protons, but also on the speed of their propagation in the interstellar medium. The TeV radiation detected by H.E.S.S. is localised within an angular diameter of several arcminutes. This implies that, for the distance to the Galactic Centre $d \simeq 8$ kpc, the linear size of the γ-ray production region can be as large as 10 pc. The density of the diffuse interstellar gas in this region is very high, $n \simeq 10^3$ cm^{-3}. The lifetime of protons in this dense environment against nuclear p-p interactions is $t_{\rm pp} \approx 5 \times 10^4$ yr. Thus, in the case of absolute confinement of protons, the γ-ray luminosity after $\sim 10^5$ years of continuous injection of protons achieves its maximum ("saturated") level, $L_\gamma = \eta \dot{W}_{\rm p}$, with an efficiency $\eta \simeq 1/3$ (the fraction of energy released in neutral π-mesons). However, the confinement time in the 10 pc region is rather limited; even in the Bohm diffusion regime the escape time of protons from this region is $t_{\rm esc} \sim R^2/r_g c \simeq 3 \times 10^5 (E/100 \text{ TeV})^{-1} (\text{B}/100 \ \mu\text{G})$ yr. Thus for any realistic diffusion coefficient $D(E)$, TeV protons leave the region before they loose their energy in p-p interactions. This not only reduces the γ-ray production efficiency but also, in the case of energy-dependent diffusion, modifies the energy distribution of the protons occupying the 10 pc region.

The impact of the energy-dependent diffusion on the resulting radiation spectra is demonstrated in Fig.4. It is assumed that over a period of 10^5 years protons are injected (quasi)continuously into the interstellar medium of density $n = 10^3$ cm^{-3}. The initial spectrum of protons is assumed to be a power-law with an exponential cutoff, $Q(E) = Q_0 E^{-\alpha} \exp(-E/E_0)$. The cutoff energy is fixed at $E_0 = 10^{15}$ eV, which is an obvious condition for effective production of γ-rays to at least 10 TeV. The choice of the power-law index depends on the assumed diffusion coefficient, if one intends to explain the energy spectrum of γ-rays detected by H.E.S.S., $J(E) = (2.5 \pm 0.21) \times 10^{-12} E^{-\Gamma}$ photons/(cm^2 s TeV) with $\Gamma = 2.21 \pm 0.09$.

The diffusion coefficient is assumed to have the following form: $D(E) = 10^{28} (E/1 \text{ GeV})^\beta \kappa$ cm^2/s. The values of $\kappa \sim 1$ and $\beta \sim 0.5$ correspond to the CR diffusion in the galactic disk. Of course, in the central region of the Galaxy one may expect significant deviation from the character of particle diffusion in "ordinary" parts of the galactic disk. In the case of effective confinement of protons, e.g. with $\kappa = 10^{-4}$ and $\beta = 0.5$, the escape time of multi-TeV protons is comparable with the characteristic time of p-p interactions. This prevents strong modification of the initial proton spectrum. Therefore, the injection spectrum of protons with power-law index $\alpha = 2.2$ fits quite well the observed TeV spectrum (curve 2 of Fig.4). Because of the effective confinement, the required injection rate of protons is rather modest, $\dot{W}_{\rm p} = 7 \times 10^{36}$ erg/s.

In the case of faster diffusion, the spectral index of injection is determined as $\alpha \simeq \Gamma - \beta$. For example, for $\kappa = 0.15$ and $\beta = 0.3$ (a diffusion regime which corresponds to Kolmogorov type turbulence), the γ-ray observations are well explained assuming the following parameters $\alpha = 1.9$ and $\dot{W}_{\rm p} = 7.5 \times 10^{37}$ erg/s (curve 1 in Fig.4).

Finally, one should note that the injection spectrum remains unchanged with very fast escape. For example, for $\kappa = 10^{-2}$ and $\beta = 1$ (an energy-dependence close to the one expected in Bohm diffusion, but with much larger diffusion coefficient), the particles propagate in the diffusion regime up to energies of several TeV. At higher energies they escape the source almost rectilinearly on timescales $R/c \sim 30$ years. This implies that while at low energies the protons inside the 10 pc region suffer significant spectral deformation, $\alpha' \to \alpha + \beta$, at very high energies the shape of the initial spectrum is essentially recovered.

Such an interesting modulation of the proton spectrum is reflected in the resulting γ-ray spectrum (curve 3 in Fig.4). In this case the requirement for the injection power of protons is higher than in the previous cases, $\dot{W}_{\rm p} = 10^{39}$ erg/s.

Although the diffuse component can be extended to distances 100 pc and beyond, because of the enhanced product of the CR and gas densities in the central 10 pc region one should expect a bright γ-ray core within several arcminutes around Sgr A*. Moreover in the case of fast diffusion (curve 3), the flux of TeV protons decreases with distance as $1/r^2$. This would result in sharp increase of relativistic protons towards the GC, and consequently to a point-like source of TeV γ-rays centered on the particle accelerator. Thus if the acceleration of protons takes place in the central black hole, this could naturally explain the existence in the H.E.S.S. data of a point-like TeV component without any indication of variability on timescales ≥ 1 hour.

4 Summary

H.E.S.S. has provided the best view so far of the Galactic Centre region in γ-rays. Whilst the origin of the γ-ray emission close to Sgr A* remains a mystery, rapid progress is being made experimentally. The accurate localisation of this central source is a key issue. H.E.S.S. data taken over the next few years promise to reduce the localisation error to the $10''$ level required to distinguish between Sgr A East and A*, the primary suspects for the particle accelerator.

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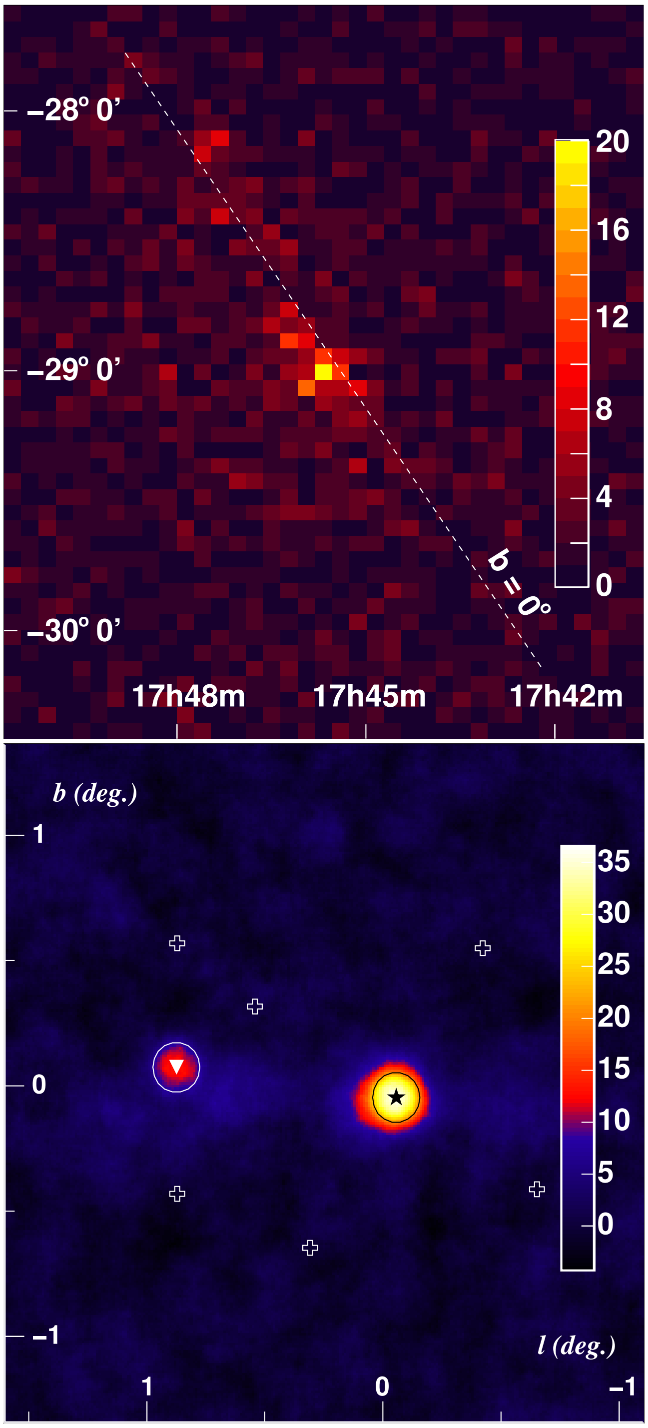

Figure 1: *Top*: a γ-ray count map of the galactic centre region derived from the H.E.S.S. 2003 data. Sgr A* lies at the centre of the map. Coordinates are RA/Declination. *Bottom:* Statistical significance of the Galactic Centre region derived from the 2004 dataset of H.E.S.S.. White crosses show the tracking positions used. G 0.9+0.1 is shown as a triangle and Sgr A* as a star. The two circles show the integration radius used in the calculation of significance. Galactic coordinates are used.

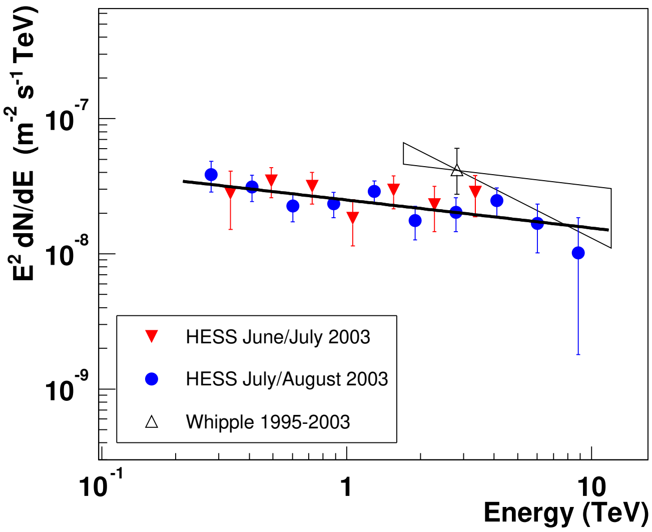

Figure 2: The γ-ray spectrum of the galactic centre as measured by the CANGAROO-II, Whipple and H.E.S.S. instruments. The Whipple data shown is the amended version taken from [5]

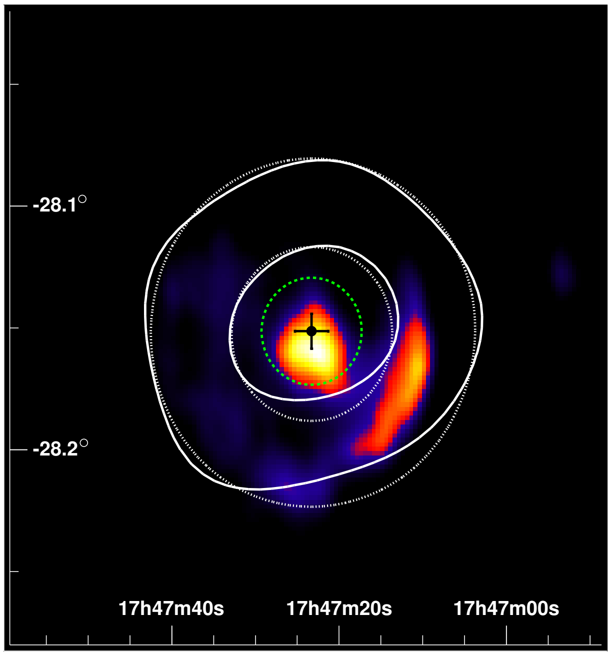

Figure 3: 90 cm radio flux map of G 0.9+0.1 from LaRosa et al. ([13]), overlayed with contours (at 40% and 80% peak brightness) of the smoothed count map of γ-ray candidates (solid lines). The point-spread function of the instrument is shown with dotted lines. The best fit position of the VHE γ-ray is shown at the centre. The innermost circle (dashed) illustrates the 95% confidence limit on the rms size of the emission region.

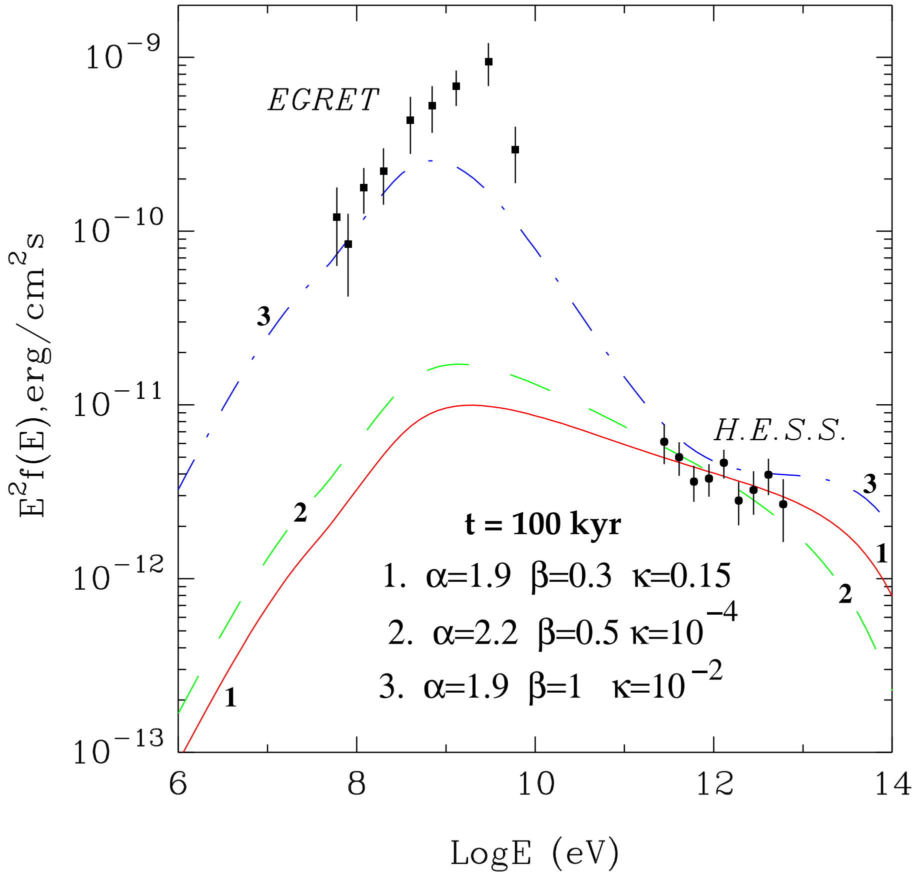

Figure 4: Energy spectra of γ-rays from pp interactions in the central 10 pc region of the Galactic Centre calculated under different assumptions concerning the proton injection spectrum and diffusion coefficients (described in the text).