

# Galactic TeV Gamma-Ray Sources: A Summary of H.E.S.S. Observations

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**Abstract.** One of the major science goals of the High Energy Stereoscopic System (H.E.S.S.) is to unravel the mystery surrounding the origin of Galactic cosmic-rays (CRs), via observations at TeV  $\gamma$ -ray energies. Over past few years, H.E.S.S. has uncovered more than a dozen Galactic sources of TeV  $\gamma$ -rays, the majority of which are extended in size and exhibit generally hard energy spectra. Discussed here are observational highlights of the H.E.S.S. Galactic source programme, which in summary has revealed; shell-like TeV morphology from two young shell-type SNRs; extended emission from the plerion MSH 15–52; Established the Galactic Centre TeV source; TeV emission from a the composite SNR G0.9+0.1; the first variable Galactic TeV source PSR B1259–63; the second TeV unidentified source HESS J1303–61 and also eight new sources from a scan of the inner Galactic plane.

## 1. Introduction

The origin of Cosmic-Rays has remained an unanswered question for nearly 100 years, and has motivated CR studies spanning more than 10 decades of energy (few GeV to  $> 10^{20}$  eV). A particular aspect of the CR spectrum concerns the origin of Galactic CRs up the knee (few PeV). In this context, observations of gamma radiation play a key role in determining CR origin. Accelerated CRs will produce  $\gamma$ -rays (and neutrinos) after interaction with local matter. Since the  $\gamma$ -ray trajectories are unaffected by interstellar/galactic magnetic fields,  $\gamma$ -rays (GeV energies and above) are a *tracer* of CR accelerators.

The detection of TeV  $\gamma$ -rays is achieved with ground-based methods. The H.E.S.S. telescopes, located in the Southern Hemisphere (Namibia 1800 m a.s.l., lat.  $-23.3^\circ$  S) employ the stereoscopic atmospheric Cherenkov imaging technique, the most sensitive technique developed so far in this field. H.E.S.S. is an array of four 13 m diameter imaging Cherenkov telescopes placed at the corners of a square (120m on a side). For each telescope, the 13 m mirrors are used to collect and focus Cherenkov photons from extensive air showers (EAS), onto a focal plane camera of 960 photomultiplier tubes or pixels. The direction and shape of the Cherenkov image can then be parametrised. By combining images from more than one telescope in the stereoscopic approach (also, at least two telescopes must be triggered by the same EAS within a 50 ns window), high

performance in terms of direction reconstruction and the rejection of the CR background are achieved. An angular resolution on an event-by-event basis of  $\sim$ few arc-minutes, and a 1% Crab flux sensitivity at the  $5\sigma$  level in just 25 hours observation are realised for H.E.S.S.. An important feature of H.E.S.S. is its large FoV. The 5 degree wide cameras provide excellent survey capabilities and this aspect was designed specifically with Galactic source studies in mind.

The analysis used for H.E.S.S. results described here follows standard methods in terms data quality criteria, image cleaning (the reduction of skynoise influences) and CR background rejection [1]. Independent analyses [21] have also been carried out on all sources, yielding consistent results. We have found that the H.E.S.S. Galactic sources generally exhibit hard energy spectra ( $dN/dE \sim E^{-\Gamma}$  where  $\Gamma \leq 2.5$ ), whereby a considerable fraction of  $\gamma$ -rays are observed for energies  $E > 0.5$  TeV. By applying so-called *hard-cuts*, optimised for these higher energies, improved sensitivity to hard-spectra sources is achieved. Hard cuts employ a minimum cut on image *size*‡ of 200 p.e. compared to the standard value of 80 p.e. The energy threshold (defined as the peak differential trigger rate for a Crab-like spectrum) is  $\sim 150$  GeV for standard cuts, and  $\sim 380$  GeV for hard cuts. In a few cases, an even higher *size* cut has been used (see MSH 15–52 results). Indeed, the search for new Galactic sources in a scan of the Galactic Plane has proceeded *a-priori* with hard cuts.

## 2. The H.E.S.S. Galactic Sources

### The Crab Nebula

The Crab Nebula is recognised as the standard candle of TeV  $\gamma$ -ray astronomy by virtue of its strong and steady flux, and has been targeted by annually by H.E.S.S. At the H.E.S.S. site the Crab is observed at zenith angles  $\geq 40^\circ$  giving a threshold (after selection cuts) of typically  $\geq 400$  GeV. H.E.S.S. achieves an excess significance on the Crab  $\sim 30\sigma/\sqrt{\text{hr}}$  with a detection rate of  $\sim 6.5 \gamma \text{ min}^{-1}$  after standard cuts. The reconstructed energy spectrum (440 GeV to 20 TeV) agrees well with previous measurements [4, 22] and is well-fitted by a pure power law:  $dN/dE = 2.86 \pm 0.06_{\text{stat}} \pm 0.57_{\text{sys}} \times 10^{-11} E^{-\Gamma} \text{ cm}^{-2}\text{s}^{-1} \text{ TeV}^{-1}$  where  $\Gamma = 2.67 \pm 0.03_{\text{stat}} \pm 0.1_{\text{sys}}$ . The integral flux above 1 TeV is  $1.71 \pm 0.04_{\text{stat}} \pm 0.34_{\text{sys}} \times 10^{-11} \text{ cm}^{-2}\text{s}^{-1}$ . There is marginal evidence for curvature in the energy spectrum which is the subject of further study.

### RX J1713.7–3946 (G347.3–0.5)

RX J1713.7–3946, discovered in the ROSAT all-sky survey[29], is a young shell-type SNR (70' diameter) that exhibits X-ray emission dominated by a non-thermal (most likely synchrotron) component [27, 33]. There is evidence that RX J1713.7–3946 is interacting with molecular clouds predominantly in the western region [15, 40]. The

‡ The total photo-electron yield contained in the Cherenkov image

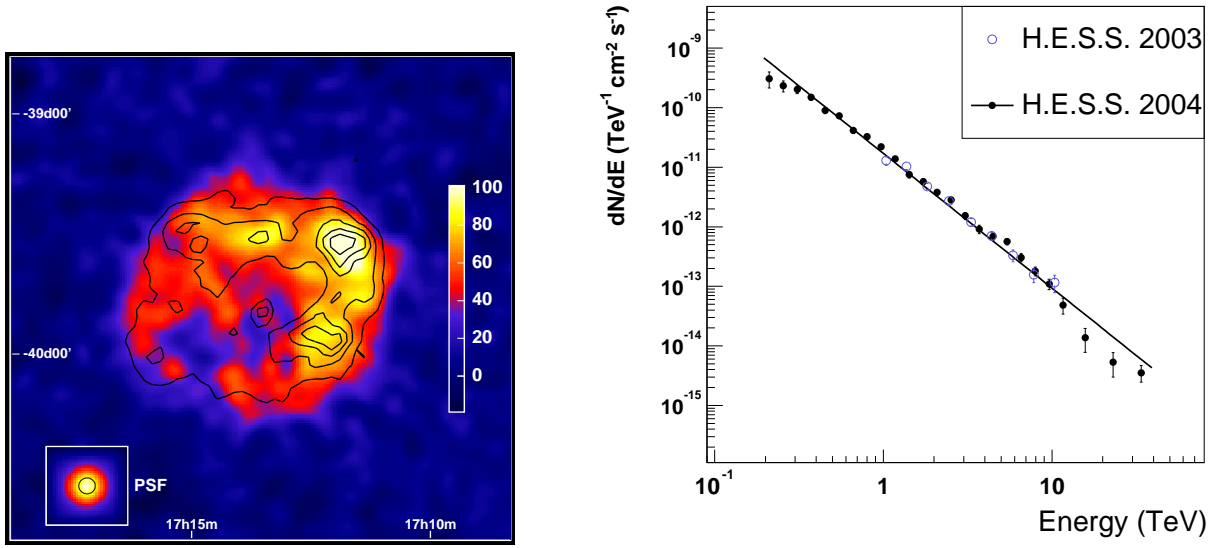
first evidence for TeV  $\gamma$ -ray emission, concentrated in the NW region, came from CANGAROO-I (& II) observations [24, 14]. H.E.S.S. observations in 2003 dramatically confirmed these results, by revealing for the first time the shell-like morphology of RX J1713.7–3946 in TeV  $\gamma$ -rays [5]. This was in fact *the first time an astrophysical object was resolved at  $\gamma$ -ray energies*. Further observations in 2004 (the total 2003 + 2004 exposure exceeds 33 hours) confirmed the shell-like structure. Figure 1 shows the excess skymap (with overlaid X-ray contours from ASCA) and energy spectrum obtained from H.E.S.S. data (2003 & 2004). The energy spectrum, when fitted with a pure power law, suggests a relatively hard spectral index of  $\Gamma = 2.27 \pm 0.02_{\text{stat}} \pm 0.20_{\text{sys}}$ . A curved or cutoff spectrum appears likely, however work is ongoing at present regarding the systematics of the highest energy points. In 2005, RX J1713.7–3946 will be observed at high zenith angles where an improved effective collecting area at high energies ( $E > 1$  TeV) will considerably increase the statistics of the higher energy points of the spectrum. Some important conclusions can be drawn from the H.E.S.S. results. The TeV morphology bears a striking resemblance to that of X-rays which may provide some hints as to the type of particles accelerated. Clearly, a high fraction of the particles are being accelerated at the shell. The energy spectrum covers more than 2 decades of energy and extends to  $40$  TeV. RXJ J1713.7–3946 is a very strong source of TeV  $\gamma$ -rays: its integrated flux (covering the entire SNR) is at the level of  $\sim 1$  Crab ( $E > 1$  TeV), and is detected at the  $\sim 40\sigma$  level.

### **RX J0852.0–4622 (G266.2–1.2) Vela Junior**

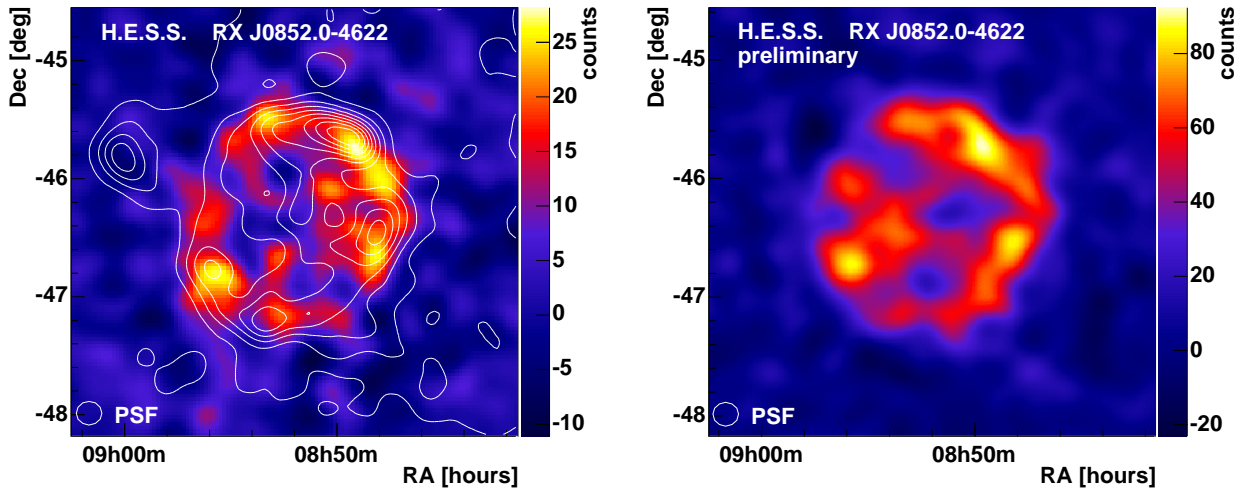
RX J0852.0–4622 (also known as Vela Junior) is another young shell-type SNR (diameter  $\sim 120'$ ) in the line of sight to the much larger Vela SNR. Its X-ray spectrum is also dominated by a non-thermal component [11, 34, 17]. TeV  $\gamma$ -rays were detected from the NW region by CANGAROO-II [20]. H.E.S.S. observed Vela Junior in 2004 for only  $\sim 3$  hours, revealing the shell-like morphology of this SNR in  $\gamma$ -rays. More recent observations from Dec 2004 to April 2005 (with  $> 10$  hours exposure) have now confirmed this global morphology (see Figure 2). The TeV morphology is similar to that of X-rays and the total  $\gamma$ -ray flux (from the entire SNR) is of order 1 Crab ( $E > 1$  TeV). The energy spectrum is hard, and is well-described by a power law with index  $\Gamma = 2.1 \pm 0.1_{\text{stat}} \pm 0.2_{\text{sys}}$  extending up to  $\sim 10$  TeV (based on 2004 data only). Vela Junior therefore appears to be somewhat similar to RXJ J1713.7–3946 in terms of its X-ray and TeV  $\gamma$ -ray characteristics.

### **The Galactic Centre Region & G0.9+0.1**

The Galactic Centre and surrounding region is rich in potential multi-TeV particle accelerators, and was one of the highest-priority targets for H.E.S.S. observations. Following the discovery of TeV  $\gamma$ -rays from this region by CANGAROO [37] and the report by Whipple [28], H.E.S.S. observations in 2003 (with a 2-telescope system;  $\sim 12$



**Figure 1.** **Left:** Excess count skymap for RX J1713.7–3946 from H.E.S.S. observations (2003 & 2004). A Gaussian smoothing ( $\sigma = 2'$ ) has been applied. The black contours indicate the ASCA-measured X-ray flux in the 1 to 3 keV band [39]. **Right:** Energy spectra from 2003 and 2004 (preliminary) H.E.S.S. data.



**Figure 2.** **Left:** Excess count skymap for RX J0852.0–4622 from 2004 H.E.S.S. observations. The white contours depict the X-ray flux (energies above 1.3 keV) from the ROSAT all-sky survey. **Right:** Excess count map (preliminary) from 2005 H.E.S.S. data. In both plots a Gaussian smoothing ( $\sigma = 6'$ ) has been applied.

hours) confirmed the existence of a TeV source [2] (labelled HESS J1745-290) at the  $+9\sigma$  level, and narrowed down its location error to about  $15''_{\text{stat}}$ . Further observations by H.E.S.S. in 2004 (with 4-telescopes; 36 hours, yielding  $> +25\sigma$ ) currently place the TeV source  $5'' \pm 10''_{\text{stat}} \pm 20''_{\text{sys}}$  from SgrA\*. The energy spectrum of HESS J1745-290 extends to  $\sim 20$  TeV and is well-fit by a pure power law with index  $\Gamma = 2.26 \pm 0.05_{\text{stat}}$ . Interestingly, the flux of HESS J1745-290, which is at the 0.1 Crab level ( $E > 1$  TeV  $I = 1.8 \times 10^{-12}$  ph cm $^{-2}$ s $^{-1}$ ) appears steady on all time-scales so-far tested (yearly to 10 minutes [31]).

Hints of a second TeV source in the Galactic Centre region (from 2003 H.E.S.S. data) were soon confirmed by the 2004 dataset [6]. This new source is positionally consistent with the composite SNR G0.9+0.1. The centrally-peaked X-ray emission of G0.9+0.1 [30] is thought to be driven by a compact object as in a pulsar-wind-nebula (PWN) scenario. The energy spectrum of G0.9+0.1 is consistent with a pure power law with an index of  $\Gamma = 2.40 \pm 0.11_{\text{stat}} \pm 0.20_{\text{sys}}$ . Its integral flux ( $E > 200$  GeV) is  $\sim 0.02$  Crab, making G0.9+0.1 one of the weakest TeV sources detected to-date.

### MSH 15-52

MSH15-52 is a composite SNR, containing a 150-ms pulsar (PSR B1509-58). The pulsar is thought to power a PWN, a surrounding SNR shell (G320.4-1.2) and a HII region (RCW 89), as seen in radio and X-rays [36]. MSH15-52 is one of the strongest-known X-ray PWN. The X-ray morphology (up to 10 keV) is elongated and roughly centred on PSR B1509-58 with two arms extending along the NW and SE directions. First claims for a TeV  $\gamma$ -ray signal ( $\sim 0.1$  Crab;  $E > 1.9$  TeV) came from CANGAROO observations [32]. H.E.S.S. observations in 2004 (22 hours) revealed a strong TeV signal ( $+25\sigma$  significance at the pulsar position alone) which is clearly extended in size (Figure 4). The TeV morphology is elongated in the NW-SE direction and is coincident with the soft X-ray (0.6-2.1 keV) emission as seen by ROSAT. This is the first detection of extended emission from a PWN at  $\gamma$ -ray energies. The energy spectrum of MSH15-52 is well-fitted by a pure power law up to  $40$  TeV with a spectral index of  $\Gamma = 2.27 \pm 0.03_{\text{stat}} \pm 0.20_{\text{sys}}$ . The integral flux above 280 GeV is  $\sim 0.15$  Crab Nebula flux above the same threshold.

### PSR B1259-63

PSR B1259-63 (SS 2883) is one of only a handful of binary systems consisting of a pulsar ( $P \sim 49$  ms) in orbit around a massive companion star (B2e spectral type) [18]. The pulsar has an eccentric orbit in which periastron occurs every  $\sim 3.4$  years. During this time (periastron  $\pm$  months), an increased possibility of episodic TeV emission has been suggested as the stellar wind from the B2e star comes in contact with the pulsar wind [35, 26, 25]. H.E.S.S. observed PSR B1259-63 from February to June 2004, designed to follow the object through its periastron passage (7th March 2004). A total of  $\sim 43$

hours of H.E.S.S. data were taken. The first detection of a TeV signal came from pre-periastron data (7 hours) [12]. Later, the full observations up to June revealed that PSRB 1259–63 is in fact an episodic source [9], the first-discovered non-steady TeV source that is Galactic in nature. Figure 5 compares the TeV light curve with concurrent radio measurements. The TeV flux appears to vary on timescales of days.

### HESS J1303–631

Shortly after the discovery of TeV  $\gamma$ -ray emission from the binary system PSR B1259–63, a second, somewhat stronger TeV source was discovered in the same FoV [10]. This new source, HESS J1303–631 is  $\sim 0.7^\circ$  south of PSR B1259–63 (Fig. 6), is a steady emitter, and is clearly extended in size (the intrinsic source size is estimated at  $0.16^\circ \pm 0.02^\circ$  assuming a Gaussian profile). The energy spectrum, when fitted with a pure power law yields an index  $\Gamma = 2.44 \pm 0.05_{\text{stat}} \pm 0.20_{\text{sys}}$ . The integral flux for energies  $E > 380$  GeV amounts to  $I = (1.2 \pm 0.2_{\text{stat}}) \times 10^{-11}$  ph cm $^{-2}$ s $^{-1}$  which is  $\sim 0.17$  Crab at the same threshold. HESS J1303–631 is positioned close to the centre of the OB stellar association Cen OB1 [23], which itself may be a site of CR acceleration. A number of molecular clouds are also well-positioned in relation to HESS J1303–631 (at distances 2.1 or 7.7 kpc and 12 kpc respectively), which could suggest that the TeV source is the result of CR interactions with local dense matter. Another interesting counterpart candidate is the pulsar PSR J1301–6305, which would imply that the TeV source results from the PWN process. Given that these associations are not completely clear, HESS J1303–631 joins the list of unidentified TeV sources, following the discovery of TeV J2032+4130 by HEGRA [3].

### Galactic Plane Scan ( $-30^\circ \geq l \leq 30^\circ$ )

A major observational programme of H.E.S.S. has been to scan the Southern Galactic Plane for new TeV sources. The inner Galactic Plane, covering longitudes  $-30^\circ$  to  $+30^\circ$ , and latitudes  $-3^\circ$  to  $+3^\circ$  was surveyed in 2004 for a total 230 hours, reaching a  $5\sigma$  sensitivity of  $\sim 0.03$  Crab flux at energies  $E > 200$  GeV. A total of eight new TeV sources were discovered (with post-trial significance exceeding  $+6\sigma$ ) (Figures 7, 8). Interestingly, all are extended in morphology (see [8] for details) and exhibit a generally hard energy spectrum (with power law photon indices in the range expected from SNRs and that of the Crab). Comparisons with multi-wavelength information are now underway. HESS J1640–465 is spatially coincident with SNR G338.3-0.0. HESS J1834–087 is spatially coincident with SNR G23.3-0.3 (W41), a  $27'$  diameter shell-type SNR. HESS J1813–137 is close to the recently published radio SNR candidate G12.8–0.0 [13, 38]. HESS J1804–216 coincides with the southwestern rim of the shell-type SNR G8.7-0.1 (W30) of radius  $26'$ . HESSJ 1825–137 lies  $13'$  from the pulsar PSR J1826–1334. A small  $5'$  diameter X-ray feature just south of the pulsar is also present [16], which is interpreted as a PWN. HESS J1616–508 is located  $9'$  from

the young hard X-ray pulsar PSR J1617–5055. For HESS J1837–069 a potential counterpart is the diffuse hard X-ray source G25.5+0.0 (which could be a PWN). HESS J1614–518 so far has no plausible SNR or pulsar counterpart and remains unidentified. This source is in the field of view of the nearby HESS J1616–508.

### 3. Summary & Conclusions

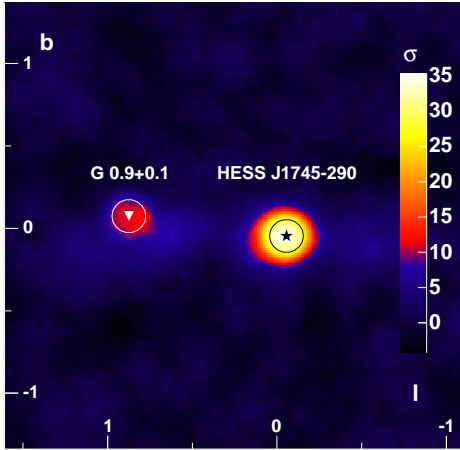
Studies of the Southern sky at TeV  $\gamma$ -ray energies have been underway for a few years now by H.E.S.S. A significant fraction of the observation programme has been devoted to the study of Galactic sources and a scan of the inner Galactic plane. Highlights from these observations include vital new information concerning previously-discovered objects and also more than 10 new sources. For the first time, shell-like morphology in TeV  $\gamma$ -rays has been established in two shell-type SNRs as well as extended emission from pulsar wind nebulae. The first episodic Galactic TeV source has been discovered and the Galactic plane scan has revealed eight new sources, all of which are extended (beyond few arc-min) in size. Many of the scan sources are in the neighbourhood of SNR which gives a clue as to their origin. Two H.E.S.S. sources have no compelling counterparts, and remain unidentified. Importantly, the majority of the H.E.S.S. sources exhibit a generally hard photon energy spectrum which extends beyond 10 TeV. These results hold important clues as to the origin of Galactic CRs.

### Acknowledgements

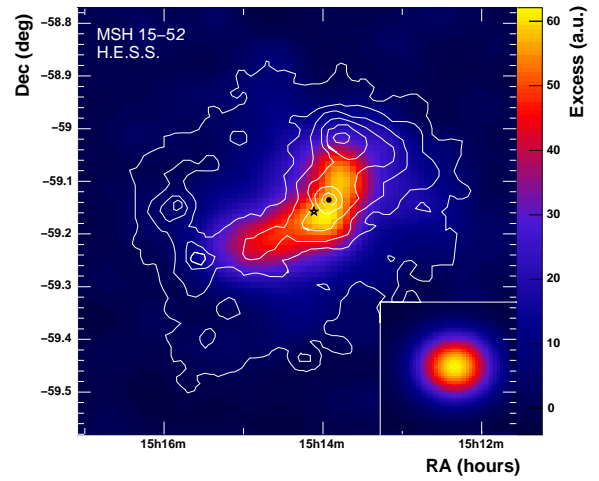
The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme of the CNRS, the U.K. Particle Physics and Astronomy Research Council (PPARC), the IPNP of the Charles University, the South African Department of Science and Technology and National Research Foundation, and by the University of Namibia. We appreciate the excellent work of the technical support staff in Berlin, Durham, Hamburg, Heidelberg, Palaiseau, Paris, Saclay, and in Namibia in the construction and operation of the equipment.

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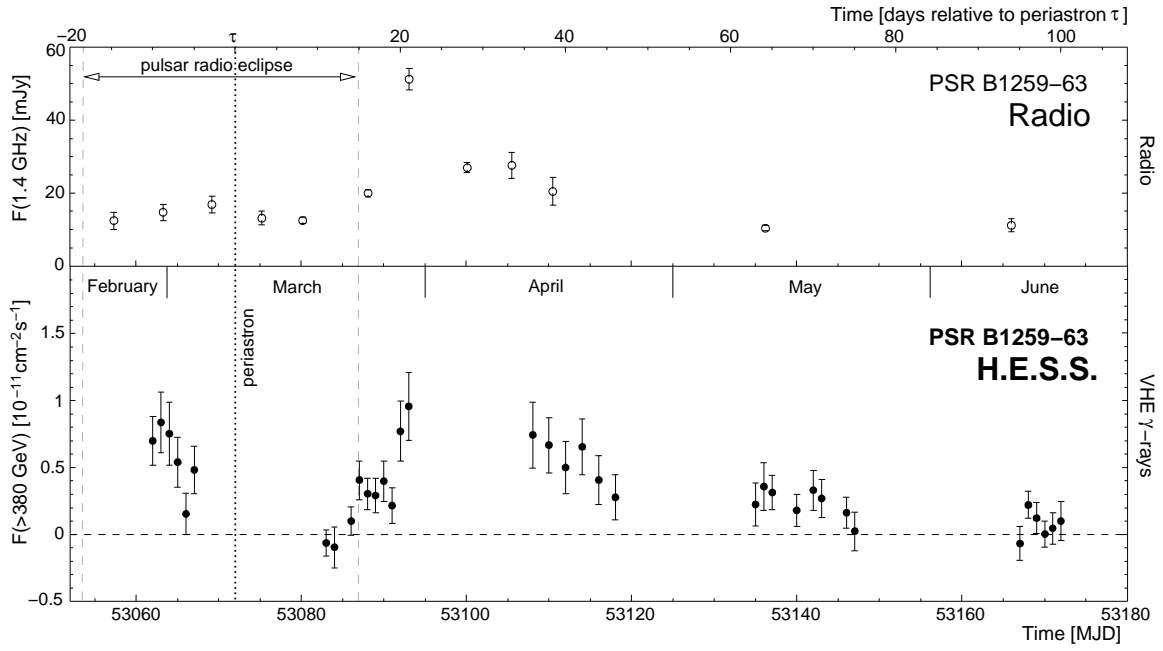
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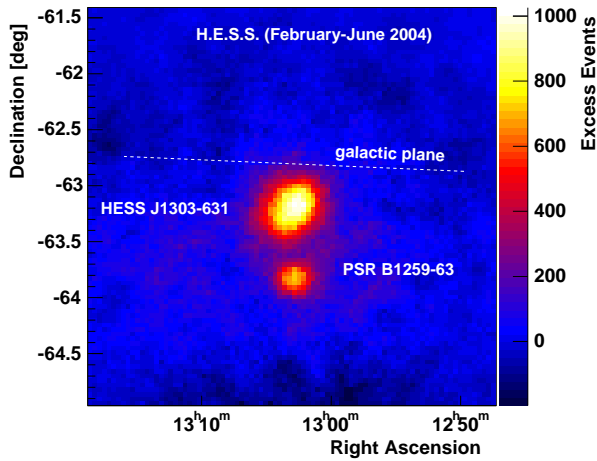
**Figure 3.** Significance skymap of the Galactic Centre region from H.E.S.S. (2004) data. The central source HESS J1745–290 and the composite SNR G.9+0.1 are clearly visible.



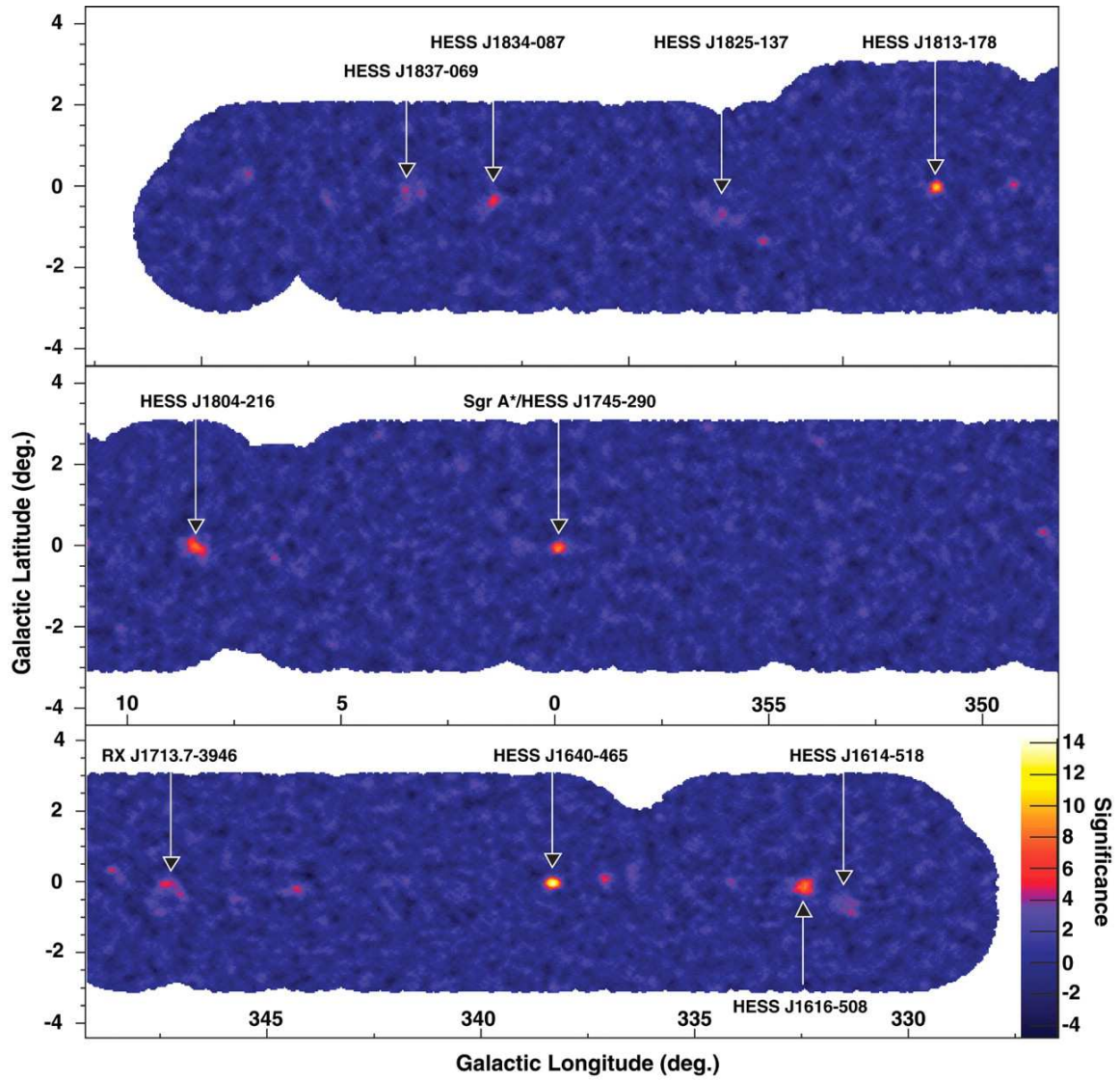
**Figure 4.** Excess map from MSH 15–52. The map is smoothed with a Gaussian of  $\sigma=0.04^\circ$  and an image *size* minimum of 400 p.e. is applied to improve the angular resolution. The white contour lines denote the X-ray (0.6–2.1 keV) count rate measured by ROSAT [36]. The black point and black star lie at the pulsar position and at the excess centroid, respectively. The right-bottom inset shows the simulated PSF smoothed identically.



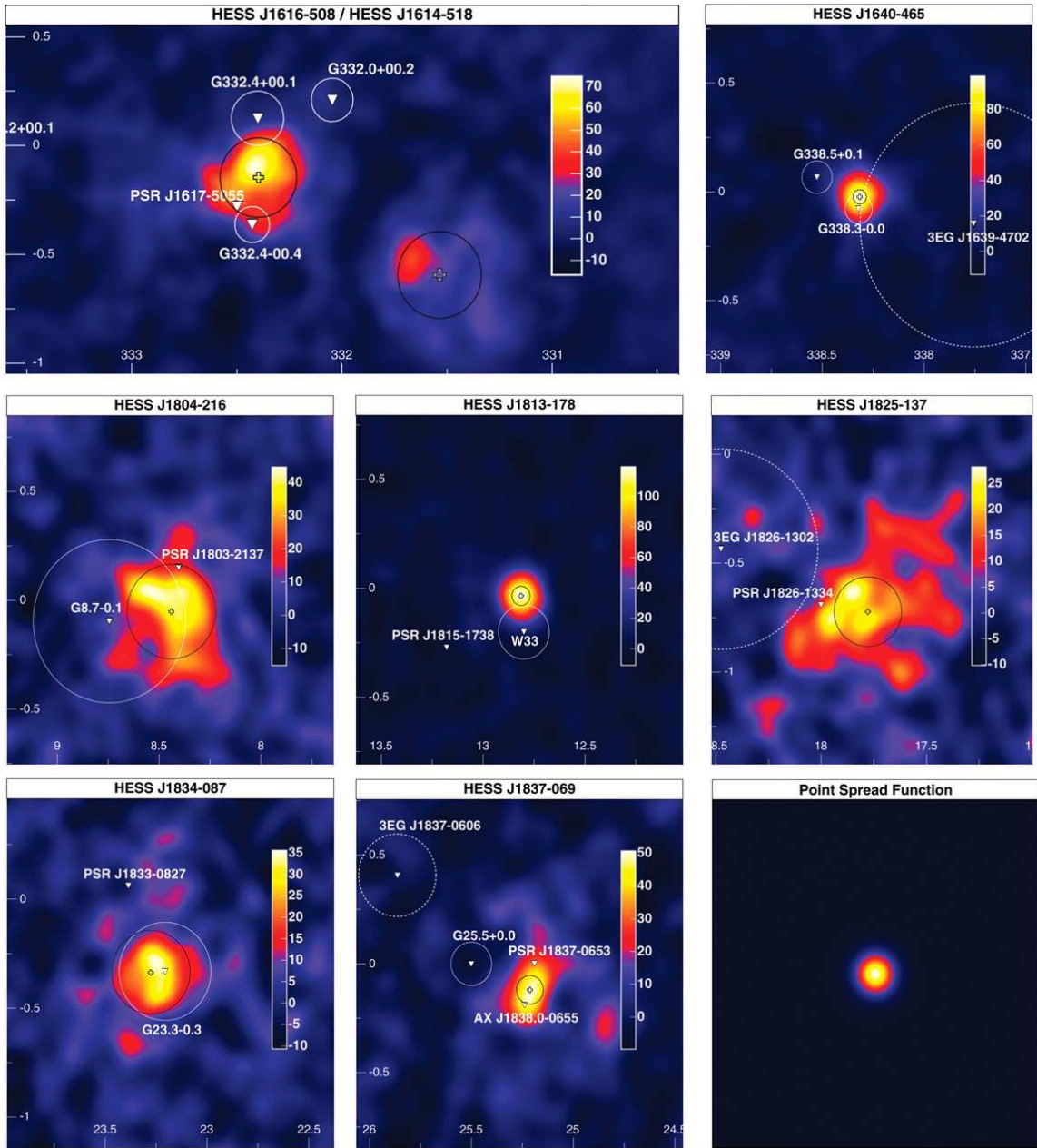
**Figure 5.** The daily TeV light curve of PSR B1259–63 (for energies  $E > 0.38$  TeV) for the period covering Feb to June 2004. Results from concurrent radio observations are also included[19].



**Figure 6.** Skymap of excess events depicting HESS J1303–631 and PSR B1259–63/SS 2883. The Galactic plane is also indicated. At each bin position events are integrated within a circle of radius  $0.14^\circ$ .



**Figure 7.** Excess significance map of the Galactic Plane scan. Extra data from re-observations of some source candidates are included. At each bin events are integrated within a circle of radius  $0.141^\circ$ .



**Figure 8.** Excess maps for each of the eight new Galactic Plane sources. A Gaussian smoothing with  $\sigma = 0.05^\circ$  has been applied. The best-fit centroids of the TeV excesses are marked by crosses, and the RMS sizes as black circles. Possible counterparts are marked as white circles. The simulated PSF is indicated in the bottom right panel, and smoothed as for other panels.