

A new population of very high energy γ -ray sources in the Milky Way

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Very high energy γ -rays probe the long-standing mystery of the origin of cosmic rays. Produced in the interactions of accelerated particles in astrophysical objects, they can be used to image cosmic particle accelerators. A first sensitive survey of the inner part of the Milky Way with the High Energy Stereoscopic System (H.E.S.S.) reveals a population of eight previously unknown firmly detected sources of very high energy γ -rays. At least two have no known radio or X-ray counterpart and may be representative of a new class of 'dark' nucleonic cosmic ray sources.

Very high energy (VHE: $E > 10^{11}$ eV) γ -rays are probes of the non-thermal universe providing access to energies far above accelerator energies on earth. The acceleration of electrons or nuclei in astrophysical sources leads inevitably to the production of γ -rays, by the decay of π^0 s produced in hadronic interactions, inverse Compton scattering of high energy electrons on background radiation fields or the non-thermal bremsstrahlung of energetic electrons. Several classes of objects in the Galaxy are suspected or known particle accelerators: pulsars and their pulsar wind nebulae (PWN), supernova remnants (SNR), microquasars, and massive star forming regions. Very high energy γ -ray sources detected so far in the Galaxy include pulsar wind nebulae, supernova remnants and objects with no identified counterpart at other energies. Such sources without counterpart are particularly interesting since a lack of X-ray emission could indicate that the primary accelerated particles are nucleons rather than the high-energy electrons. Essentially all potential Galactic sources cluster along the Galactic plane. Thus, a systematic survey of the Galactic plane is the best means to investigate the properties of these source classes and to search for yet unknown types of Galactic VHE γ -ray emitters.

Large-scale γ -ray surveys in the TeV energy regime (1 TeV = 10^{12} eV) have been performed using the Milagro water-Cherenkov detector (1) and the Tibet air-shower array (2). These all-sky instruments have only modest sensitivity, reaching a flux limit comparable to the flux level of the Crab Nebula, $\sim 2 \times 10^{-11}$ cm $^{-2}$ s $^{-1}$ (for $E > 1$ TeV), in one year of observations. Both surveys covered $\sim 2\pi$ steradian of the northern sky and resulted only in flux upper limits. A survey of the part of the Galactic plane accessible from the northern hemisphere ($-2^\circ < l < 85^\circ$, where l denotes Galactic longitude) was performed by the stereoscopic HEGRA array of imaging Cherenkov telescopes (3). No sources of VHE γ -rays were found in this survey but upper limits between 15% of the Crab flux for Galactic longitudes $l > 30^\circ$ and more than 30% of the Crab flux in the inner part of the Milky Way were derived (4). Until the completion of the High Energy Stereoscopic System (H.E.S.S.) (5) in early 2004, no VHE γ -ray survey of the southern sky, or of the central region of the Galaxy had been performed. The central part of the Galaxy contains the highest density of potential γ -ray sources. We have conducted a survey of this region with H.E.S.S. in 2004, at a flux sensitivity of 3% of the Crab flux.

H.E.S.S. is an array of telescopes exploiting the imaging Cherenkov technique. The telescopes image the Cherenkov light emitted by atmospheric particle cascades initiated by γ -rays or cosmic-rays in the upper atmosphere. Measurements of the same cascade by multiple telescopes allow improved rejection of the cosmic-ray background and better angular and energy resolution in comparison to single dish telescopes. H.E.S.S. consists of four atmospheric Cherenkov telescopes, each with 107 m 2 of mirror area (6) and equipped with a 960 pixel photo-multiplier tube camera (7). The four telescopes are operated in a stereoscopic mode with a system trigger (8), requiring at least two telescopes to provide images of each cascade. H.E.S.S. has the largest field of view (5° diameter) of all presently operating imaging Cherenkov telescopes, which yields a considerable advantage for surveys (9).

H.E.S.S. provides unprecedented sensitivity to γ -rays above 100 GeV, below 1% of the flux from the Crab Nebula for long exposures. This sensitivity has already been demonstrated by high-significance detections of the Galactic centre (HESS J1745-290) (10) and the supernova

remnant RXJ1713.7-3946 (11). The angular resolution for individual γ -rays is better than 0.1° , allowing a source position error of $30''$ to be achieved, even for relatively faint sources.

We scanned the inner part of the Galactic plane (Galactic longitude $-30^\circ < l < 30^\circ$ and latitude $-3^\circ < b < 3^\circ$) with H.E.S.S. from May to July 2004. Observations of 28 minute duration were made in steps of 0.7° in longitude and steps of 1° in latitude for a total observation time of 112 hours. An average 5 standard deviation detection sensitivity of 3×10^{-11} photons $\text{cm}^{-2} \text{s}^{-1}$ above 100 GeV ($\approx 3\%$ of the Crab Flux) was reached for points on the Galactic plane. Seven promising candidate sources from the survey were re-observed from July to September for typically 3.5 hours per source.

Eight unknown VHE sources are detected at the level of larger than 6 standard deviations after accounting for all trial factors (see **Fig. 1** and Table 1). The known VHE sources HESS J1745-290 (at the Galactic Centre) and RXJ1713.7-3946 are also detected in the scan data. The analysis used the standard H.E.S.S. analysis procedure, optimised for point-like sources (12).

It should be noted that the significance values shown in Fig. 1 (and S_3 of Table 1) do not directly reflect the probability that a given signal represents a γ -ray source, because the large number of search points in the sky map (250000) enhance the chance for statistical fluctuations to mimic a signal. Probabilities must be scaled by a *trial factor* accounting for the number of attempts to find a source, here conservatively assumed to be equal to the number of points in the sky map. Simulations of randomly generated sky maps without γ -ray sources show that the effective number of trials is smaller than the number of points, due to correlations between adjacent search points, which are more closely spaced than the instrumental width of the point spread function. Trial factors apply only for the initial search, where source candidates were identified (S_1 , before trials), but not for follow-up observations, where the significance (S_2) of a signal was evaluated assuming the position derived from the initial search. The scaled-down significance from the initial search and the result of the follow-up observations were combined by summation in quadrature to give a final detection significance (S_4).

Since most sources appear moderately extended, S_5 in Table 1 lists the significance similar to S_4 but assuming extended sources. For each of these candidates a spectral analysis was performed and Table 1 also gives the best fit flux above 200 GeV.

For the purpose of source size and position fitting, an additional cut requiring an image size exceeding 200 photoelectrons in each camera was applied. This cut further suppresses the cosmic-ray background (by a factor of ~ 7), at the expense of reduced statistical significance and increased energy threshold (250 GeV). It also improves the angular resolution by 30%. After applying this cut the spatial distribution of excess events for each candidate was fit to a model of a 2-D Gaussian γ -ray emission region (Table 1) convolved with the point spread function of the instrument (derived from Monte Carlo simulations and verified by observations of the Crab Nebula).

The new Galactic VHE γ -ray emitters cluster close to the Galactic plane (with a mean b of -0.25° and an rms of 0.25°) (**Fig. 2**). This is a clear indication that we see a population of Galactic (rather than extragalactic) sources. Furthermore, the observed distribution resembles

Name	Position		Size σ (arcmin.)	Significance					Flux
	l	b		S_1	S_2	S_3	S_4	S_5	
HESS J1614-518 [†]	331.54°	-0.59°	12	5.2	4.3	6.7	4.7	6.8	9
HESS J1616-508	332.40°	-0.15°	11	7.4	8.9	11.6	10.5	12.8	17
HESS J1640-465	338.32°	-0.02°	2	11.7	8.3	14.3	13.4	11.5	19
HESS J1804-216	8.44°	-0.05°	13	8.2	5.9	10.1	8.8	9.6	16
HESS J1813-178	12.81°	-0.03°	3	10.2	8.3	13.2	12.2	8.9	12
HESS J1825-137 [†]	17.78°	-0.72°	10	4.4	3.7	5.8	3.7	6.5	9
HESS J1834-087	23.28°	-0.34°	12	6.7	5.6	8.7	7.2	7.8	13
HESS J1837-069	25.21°	-0.12°	4	6.0	6.0	8.4	6.9	6.4	9

Table 1: Characteristics of the new γ -ray sources. Position: Galactic Longitude (l) and Latitude (b) with a statistical error in the range of 1-2 arcmin. Size: estimated source extension σ for a brightness distribution of the form $\rho \propto \exp(-r^2/2\sigma^2)$ with a statistical error in the range of 10-30%. S_1 : Significance for a point source cut of $\theta^2 = 0.02$ degrees², using scan data only, without correction for the number of trials. S_2 : As for S_1 but only including follow-up observations of this source (no correction needed). S_3 : Significance of combined scan and follow-up observations (as shown in **Fig. 1**). S_4 : As S_3 but including a correction for the number of trials ($n = 250000$). S_5 : As for S_4 but with an extended cut of $\theta^2 = 0.05$ degrees² Flux: Estimated flux above 200 GeV ($\times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$) with a statistical error between 10-35%. [†]: These sources were re-observed within the field of view of dedicated observations of another target.

that of Galactic SNRs (15) and of energetic pulsars ($\dot{E} > 10^{34}$ erg/s) (16). However, due to the non-uniform exposure of the scan, and the unknown luminosity distribution of the parent population, we cannot make a quantitative statement on the compatibility of these distributions.

All of the sources are significantly extended beyond the size of the H.E.S.S. point spread function. As the search described here was optimised for point-like sources it is likely that several more significant sources with an extended nature exist in this dataset. We note that the new sources mostly have spectra with rather hard photon indices in the range between the one expected for SNRs and that of the Crab Nebula.

We have searched for counterparts for the new γ -ray sources in other wavelength bands. **Fig. 3** shows the γ -ray emission from the region around each source together with potential counterparts. While the chance probability for spatial coincidences with SNR in the region of the scan is not negligible (6%), plausible associations exist for three of the new sources with an SNR: for HESS J1640-465, HESS J1834-087 and HESS J1804-216. **HESS J1640-465** is spatially coincident with the SNR G338.3-0.0, which is a broken shell SNR lying on the edge of a bright ultra-compact HII region (15). This HII region could conceivably provide target material for nuclear particles accelerated in the SNR, generating VHE γ -rays by π^0 decay. The unidentified EGRET source 3EG J1639-4702 (17) lies 35' away and could also be connected to HESS J1640-465, given the position uncertainty of 34' of the EGRET source. **HESS J1834-087** is spatially coincident with SNR G23.3-0.3 (W 41), a 27' diameter shell-type SNR (18). **HESS J1804-216** coincides with the southwestern rim of the shell-type SNR G8.7-0.1 (W30) of radius 26'. From CO observations (19), the surrounding region is known to be associated

with molecular gas where massive star formation is taking place. This SNR could be associated with the nearby (25 arcminutes), young pulsar PSR J1803-2137 (20).

HESS J1804-216 is one of three plausible associations with nebulae powered by sufficiently energetic young pulsars. The others are HESS J1825-137 and HESS J1616-508. **HESS J1825-137** lies 13' from the pulsar PSR J1826-1334 which has been associated with the close-by unidentified EGRET source 3EG J1826-1302 (21). A 5' diameter diffuse emission region extending asymmetrically to the south of the pulsar was detected using XMM (22). This diffuse emission is interpreted as synchrotron emission produced by a pulsar wind nebula (PWN). The VHE emission is similarly located south of PSR J1826-1334, and could be coincident with the PWN. The conversion efficiency implied from spin down power to VHE γ -rays is less than 1%. **HESS J1616-508** is located in the middle of a complicated region 9' from the young hard X-ray pulsar PSR J1617-5055 (23). The VHE γ -ray flux is again less than 1% of the spin-down luminosity of the pulsar. 13' away lies the SNR G332.4-0.4 (RCW 103) (15) which harbours a compact X-ray source (1E 161348-5055) (24) and the SNR G332.4+0.1 (Kes 32) (25), but none of these SNRs is spatially coincident with the VHE emission. It should be noted that none of the discussed SNR or PWN associations currently meet the criteria necessary for promotion to counterparts. Counterpart identification requires positional agreement with an identified source, a plausible γ -ray emission mechanism and consistent multi-frequency behaviour.

For **HESS J1837-069** a potential counterpart is the diffuse hard X-ray source G25.5+0.0, which is 12' across and was detected in the ASCA Galactic plane survey (26). The nature of this bright X-ray source is unclear but it may be an X-ray synchrotron emission dominated SNR such as SN 1006 or a PWN. The brightest feature in the ASCA map (AX J1838.0-0655), located south of G25.5+0.0, coincides with the centre of gravity of the VHE emission and is therefore the most promising counterpart candidate. This still unidentified source was also serendipitously detected by BeppoSAX and also in the hard X-ray (20-100 keV) band in the Galactic plane survey of Integral (27).

For the two remaining sources HESS J1813-178 and HESS J1614-518, no plausible counterparts have been found at other wavelengths. **HESS J1813-178** is not spatially coincident with any counterparts in the region but lies 10' from the centre of the radio source W 33. W 33 extends over 15' with a compact radio core (G12.8-0.2) which is 1' across (28). The region is highly obscured and has indications of recent star formation (29). In its extended emission and location close to an OB association, HESS J1813-178 resembles the unidentified TeV source discovered by HEGRA, TeV J2032+4130 (30) and the first H.E.S.S. unidentified γ -ray source HESS J1303-63 (31). **HESS J1614-518** has no plausible SNR or pulsar counterpart. This source is in the field of view of HESS J1616-508 which is located nearby ($\sim 1^\circ$ away). The lack of any counterparts for these two sources suggests the exciting possibility of a new class of 'dark' particle accelerators in the Galaxy.

In conclusion, we have on the basis of the survey generated a first unbiased catalogue of very high energy γ -ray sources in the central region of our Galaxy, extending our multi-wavelength knowledge of the Milky Way into the VHE domain. Three of the eight newly discovered sources are potentially associated with supernova remnants, two with EGRET sources. In three cases an

association with pulsar-powered nebulae is not excluded. At least two sources have no identified counterpart in radio or X-rays, which suggests the exciting possibility of a new class of ‘dark’ nucleonic particle accelerators. This catalogue provides insights into particle acceleration in our galaxy and adds a piece to the long-standing puzzle of cosmic-ray origin.

References and Notes

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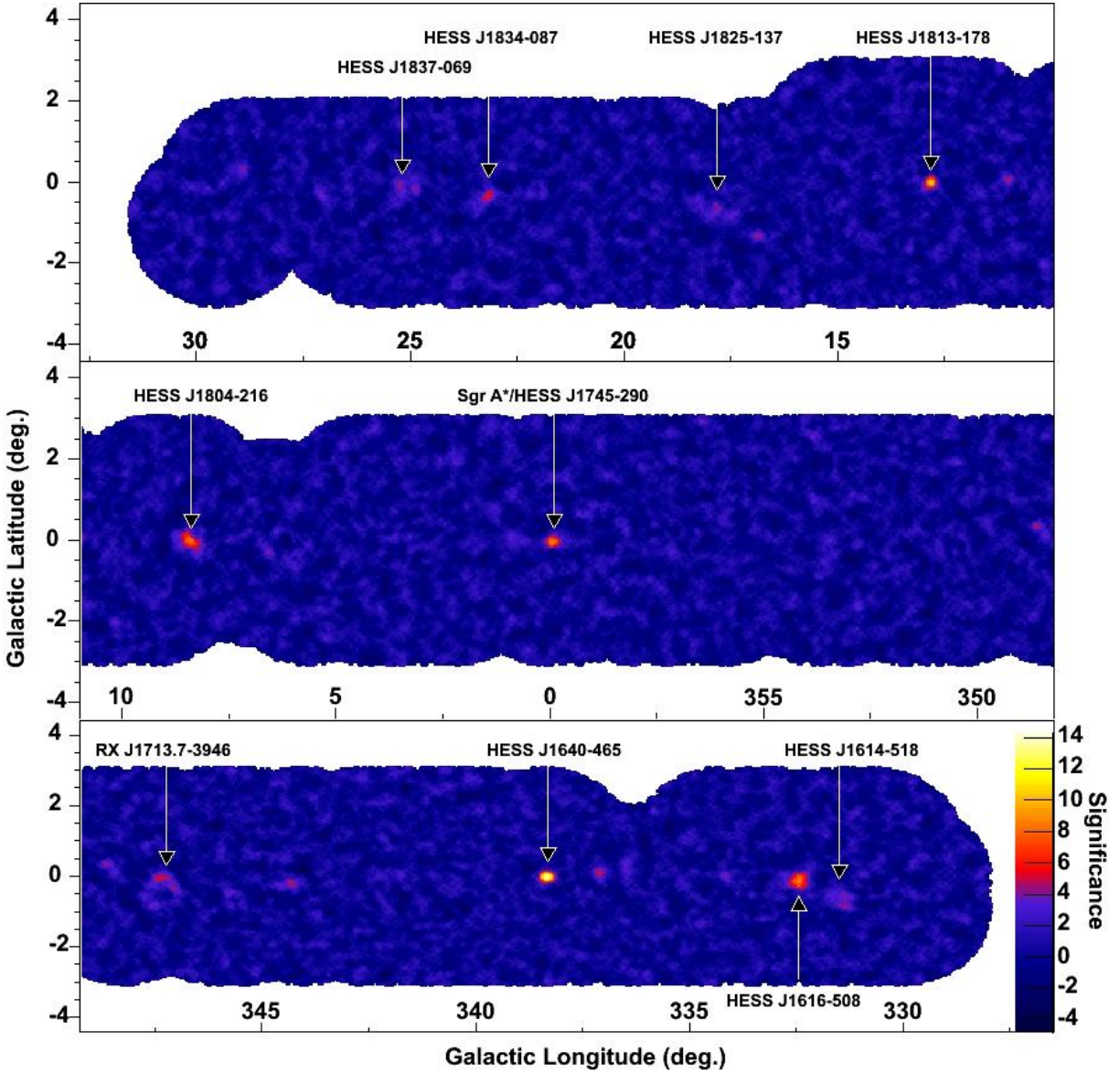


Figure 1: Significance map of the H.E.S.S. 2004 Galactic plane scan. Re-observations of candidates from the initial scan are included here. The background level was estimated using a ring around the test source position (12). On-source counts are summed over a circle of radius θ , where $\theta^2 = 0.02$ degrees², a cut appropriate for point-like sources. To calculate the significances, it is necessary to correct for the relative acceptance and area of the on and off regions. The correction is given by a run-wise radially symmetric acceptance function, which describes the background at the 1% level. Events falling up to 2° from the pointing direction of the system are used. At this angle the γ -ray acceptance efficiency has decreased to 20% of its peak value. After acceptance correction the approach of Li and Ma (13) is used to calculate the significance at every point on the map. We note that consistent results are obtained for these 8 sources using a completely independent calibration and analysis chain (14).

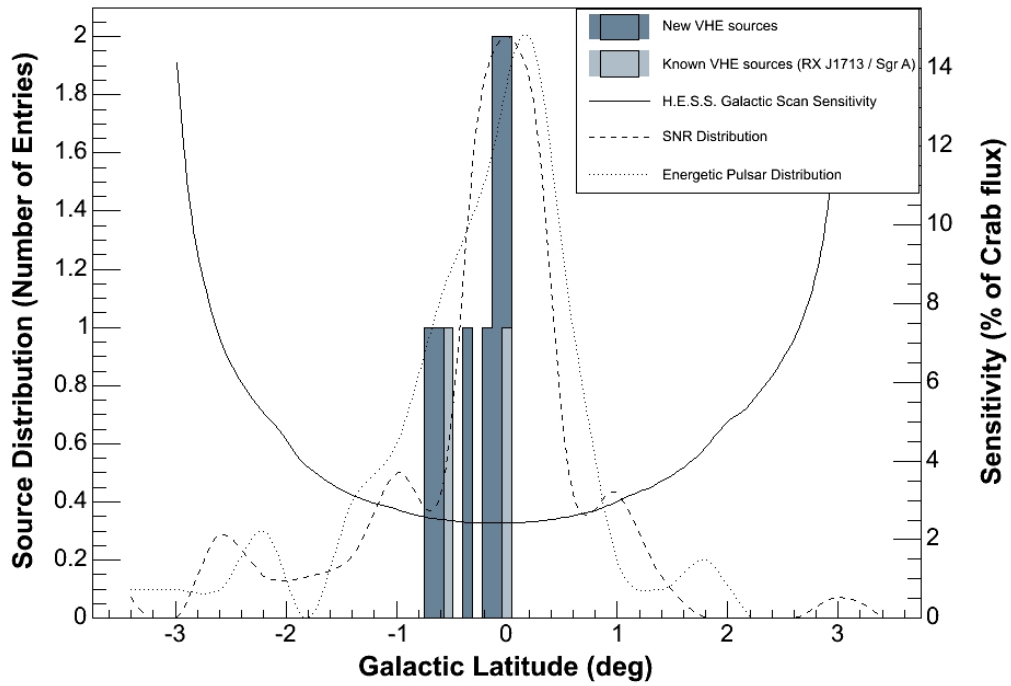


Figure 2: Latitude distribution of the eight new VHE γ -ray sources (and two known sources in the scan region), along with the average sensitivity of the H.E.S.S. Galactic plane scan (for a 5σ detection, expressed as a percentage of the flux from the Crab Nebula). The distribution of Galactic supernova remnants and of energetic pulsars (including only pulsars with spin-down luminosity \dot{E} more than 10^{34} erg/s.) are shown for comparison (for both distributions only objects within the longitude range of the HESS survey ($-30^\circ < l < 30^\circ$) were selected).

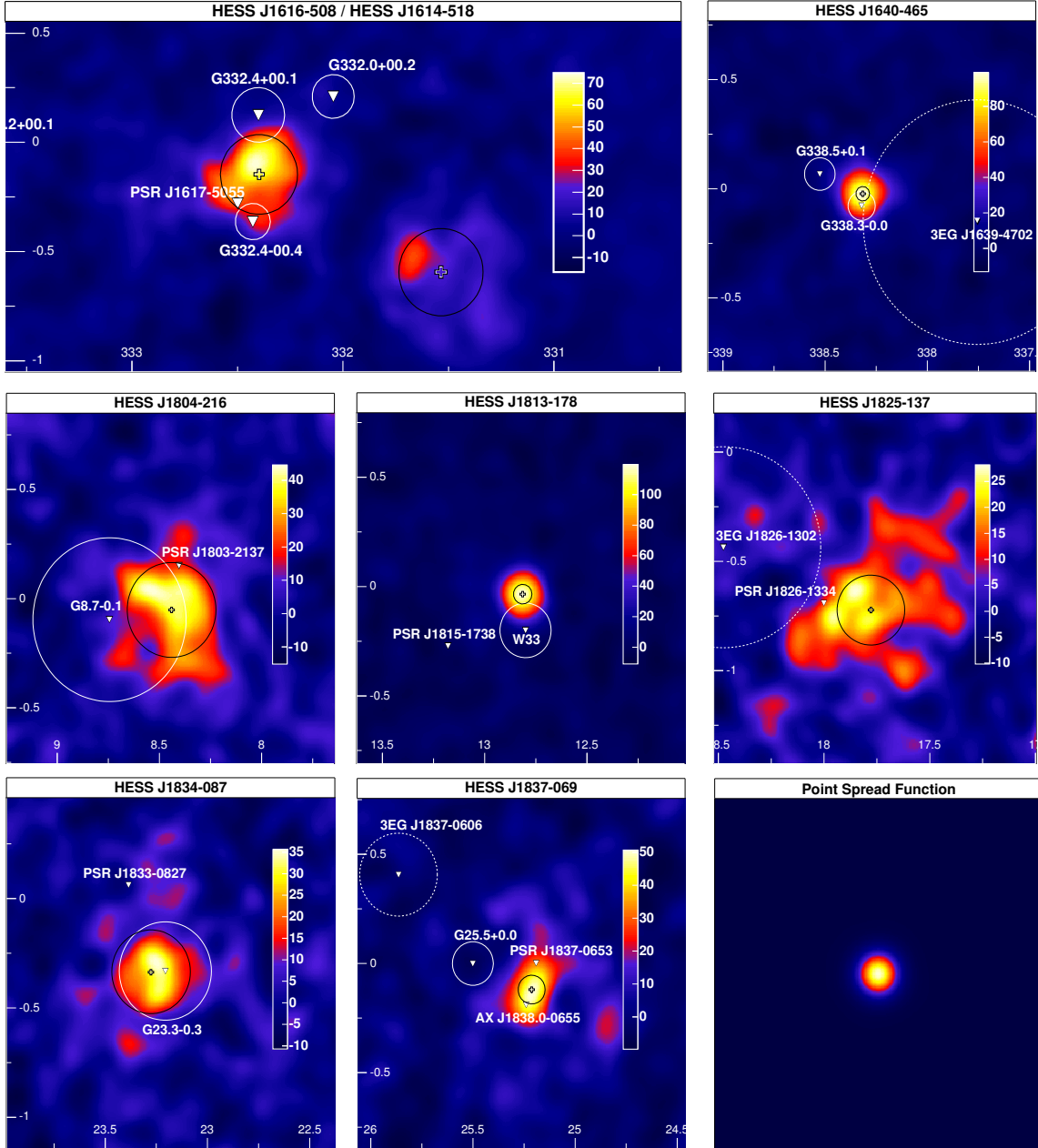


Figure 3: Smoothed excess maps in units of counts of the regions around each of the eight new sources in Galactic coordinates in degrees. An image size cut (> 200 photoelectrons) has been applied to reduce the background level and improve the angular resolution. A Gaussian of rms 0.05° is used for smoothing to reduce the impact of statistical fluctuations. The best-fit centroids for the γ -ray emission are shown as crosses, and the best-fit rms size as a black circle. Possible counterparts are marked by white triangles, with circles indicating the nominal source radius (or the position error in the case of EGRET sources). The lower right panel indicates the simulated point spread function of the instrument for these data, smoothed in the same way as the other panels.