Future Pulsar Observations with H.E.S.S.

April 25th, 2003

Alexander Konopelko, MPI-K, HD

Plan

- Introduction: What is a Pulsar?
- Models of high energy pulsars
- Current sample of pulsars
- EGRET pulsars
- VHE Gamma-rays from Pulsars (Pulsars/Plerions)
- H.E.S.S. Project
  - Experiment
  - Science with H.E.S.S.
- H.E.S.S targets:
  - Established high energy pulsars
  - Millisecond pulsars
  - Unidentified EGRET sources
  - Parkers Pulsars
- Summary: What can we learn ?

Pulsar

Formation of NS

One teaspoonful would weight a billion tons !

time

Progenitor star: ~ 8-10 $M_\odot$

Radius: $R_0 \sim 10^{11} cm$

Rotating period: $P_0 \geq 10^6 s$

Gravitational collapse

Supernovae explosion

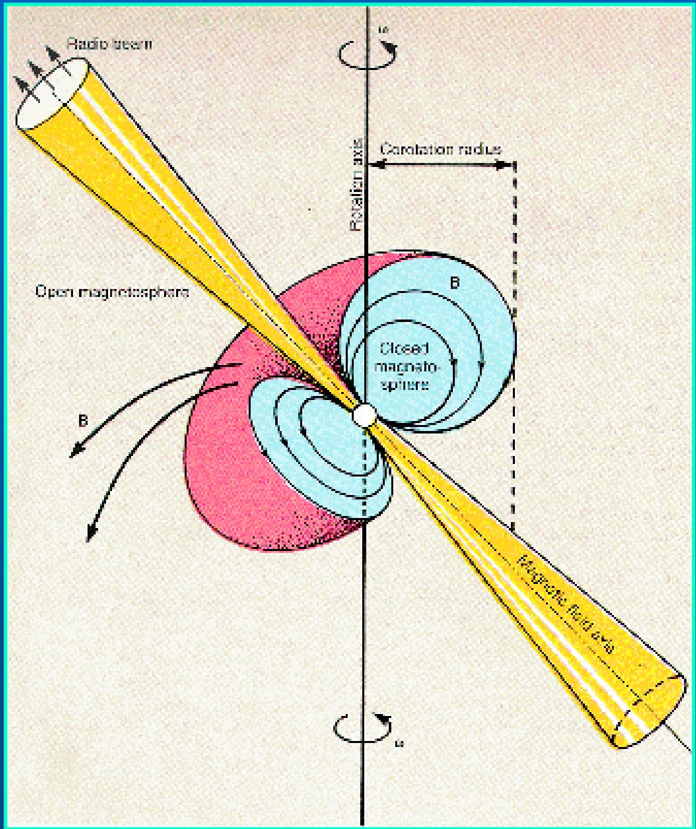
Supernovae remnant

Neutron star

Mass: $\sim 1.4\ M_\odot$

Radius: $10\ km$

Pulsar parameters



Pulsar is rotating neutron star

Period:

$$P_{NS} \sim P_0 \left(\frac{a}{R_0}\right)^2 \geq 10^{-3} \div 10^{-4}\, s$$

Pulsars are gradually slowing down

Loss of rotational energy:

$$\dot{E} = -(2\pi)^2 I \dot{P} / P^3$$

Typical pulsar:

$P \sim 1s$ $\quad \dot{P} \sim 10^{-15}\, s \cdot s^{-1}$ $\quad I \sim 10^{45}\, gm \cdot cm^2$

$$\dot{E} \sim 4 \times 10^{31}\, erg \cdot s^{-1} (i)$$

Magnetic dipole radiation: Ostriker & Gunn (1969)

$$\dot{E} = \left(\frac{2}{3}\right) B^2 a^6 \Omega^4 / c^3 \quad (ii)$$

Ω - angular velocity, a - radius of neutron star

Equating (i) & (ii):

$$B_s \sim 3.2\times10^{19} (P\dot{P})^{1/2} \sim 10^{12}\,G$$ (surface magnetic field)

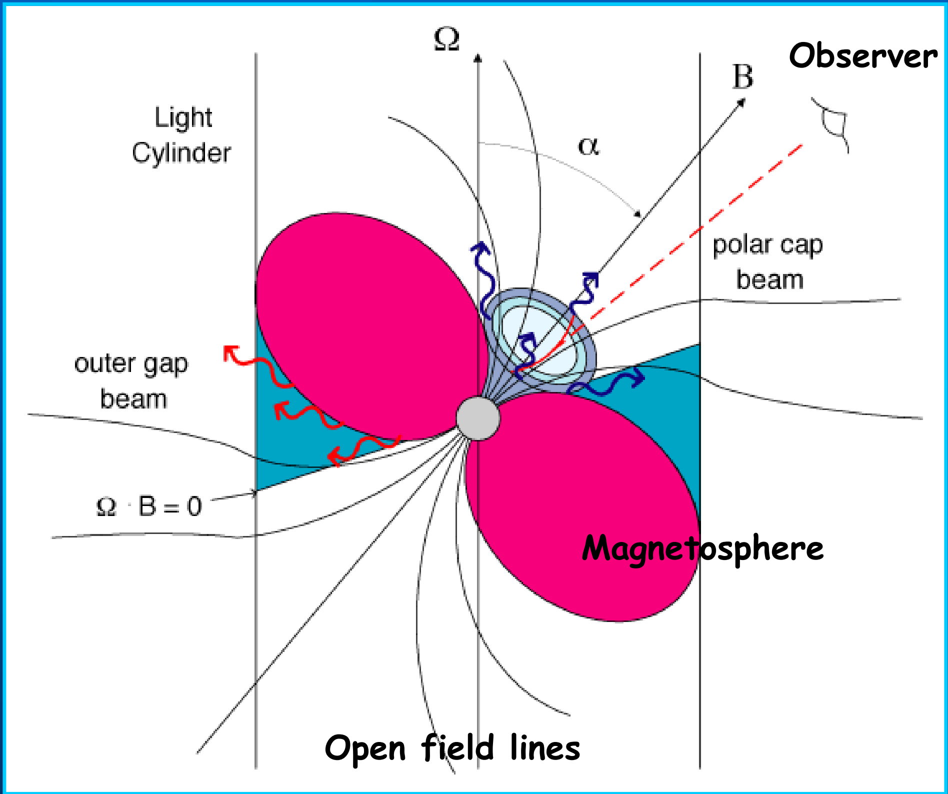
Characteristic age:

$$\tau = \left(\frac{1}{2}\right)\left(\frac{P}{\dot{P}}\right) \sim 16\times10^{6}\ years \qquad (B = const)$$

Pulsars are the objects with extreme physics environment !

Discovery: 1967, Cambridge, research student Jocelyn Bell &
observatory director Anthony Hewish
Hewish et al (1968) detected in radio PSR B1919+21

Polar Cap Model



Rotating, magnetized neutron star generates huge electric field:

$$E \sim v \times B$$

Goldreich & Julian (1969) Electrostatic forces overcome gravity

$$I_{GJ} \sim B_s / P^2$$

Becker & Trümper (1997) surface *T* could exceed thermal emission *T*

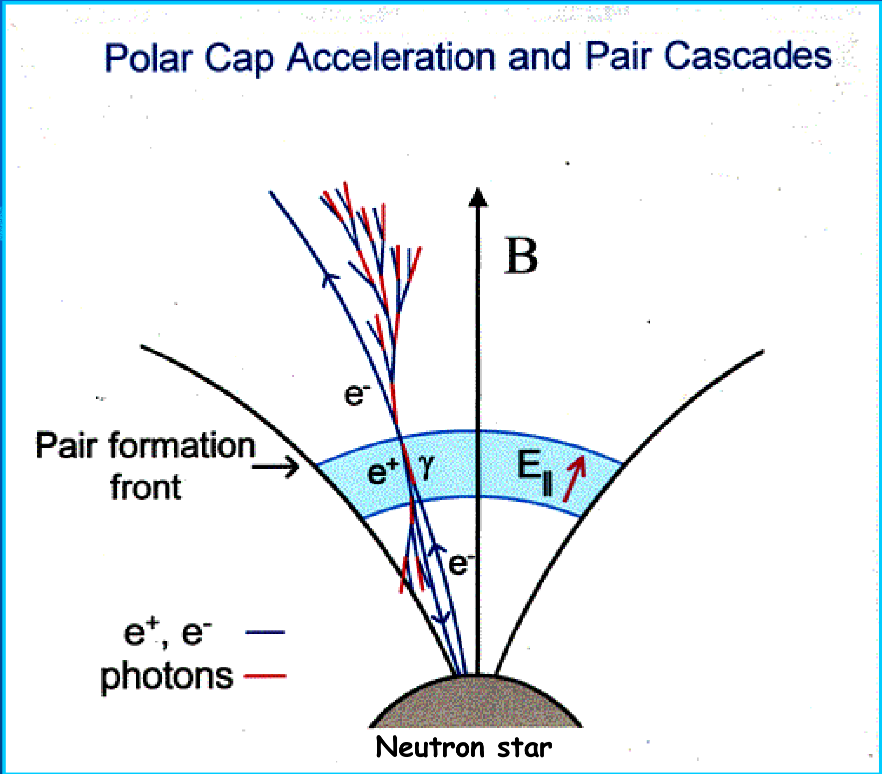
$$T_s \sim 10^5 - 10^6 K \geq T_e(T_i)$$

Field lines crossing light cylinder (open field lines) originate at two polar caps of radius

$$R_{LC} \equiv c / \Omega$$

$$r_{pc} \approx a\theta_{pc} \approx \left(\frac{\Omega a^3}{c}\right)^{1/2} \sim 8 \times 10^4 cm$$

$$(\theta_{pc} \cong 4.6^o)$$



(Courtesy of Alice Harding)

Sturrock (1971); Harding (1981);
Daugherty & Harding (1982)

- Acceleration of electrons
- Cooling mechanisms
  - (i) Inverse Compton of X-rays
  - (ii) Curvature radiation
- Creation of pair cascade

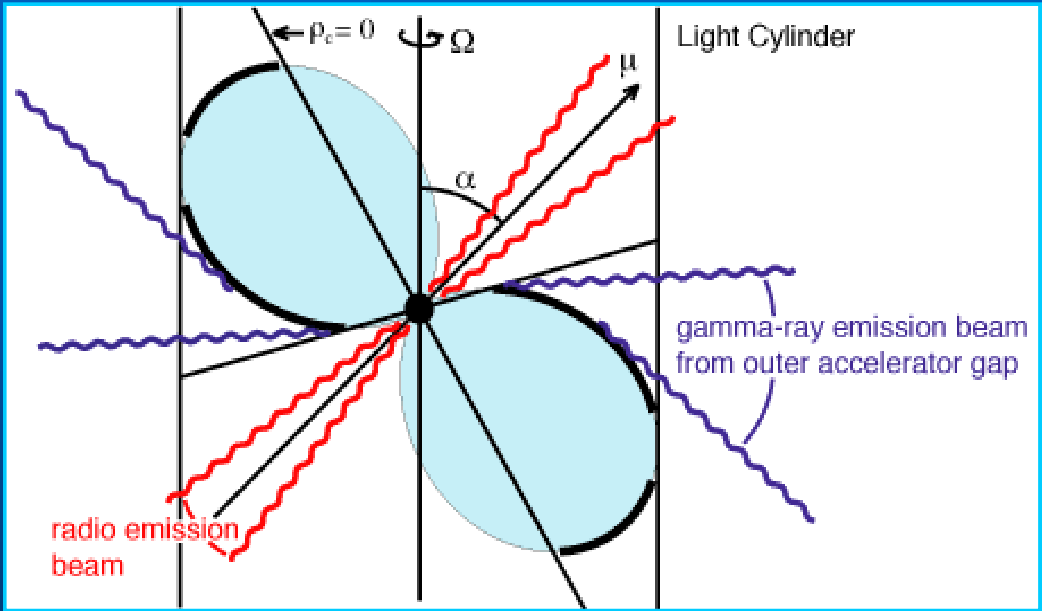
$\gamma \rightarrow e^+ e^-$ $\quad \varepsilon \geq \varepsilon_{th} = 2m_e c^2 / \sin\theta_{kB}$

$\gamma \rightarrow \gamma\gamma$ $\quad (B \geq 10^{14}\,G)$

Pair formation front ~ 0.5-1 stellar radii
No. of generations: 3-4
No. of pairs per electron: $\sim 10^3 - 10^4$

Polar Cap model predicts super exponential cutoff in the high energy Gamma-ray spectra !

Outer Gap Model



Cheng, Ho & Ruderman (1986);
Romani (1996)

Vacuum gap in outer magnetosphere

$$\Omega \cdot B \equiv 0$$

Charges escape through LC no charges coming through null charge surface

Curvature photons interacts with non-thermal X-rays:

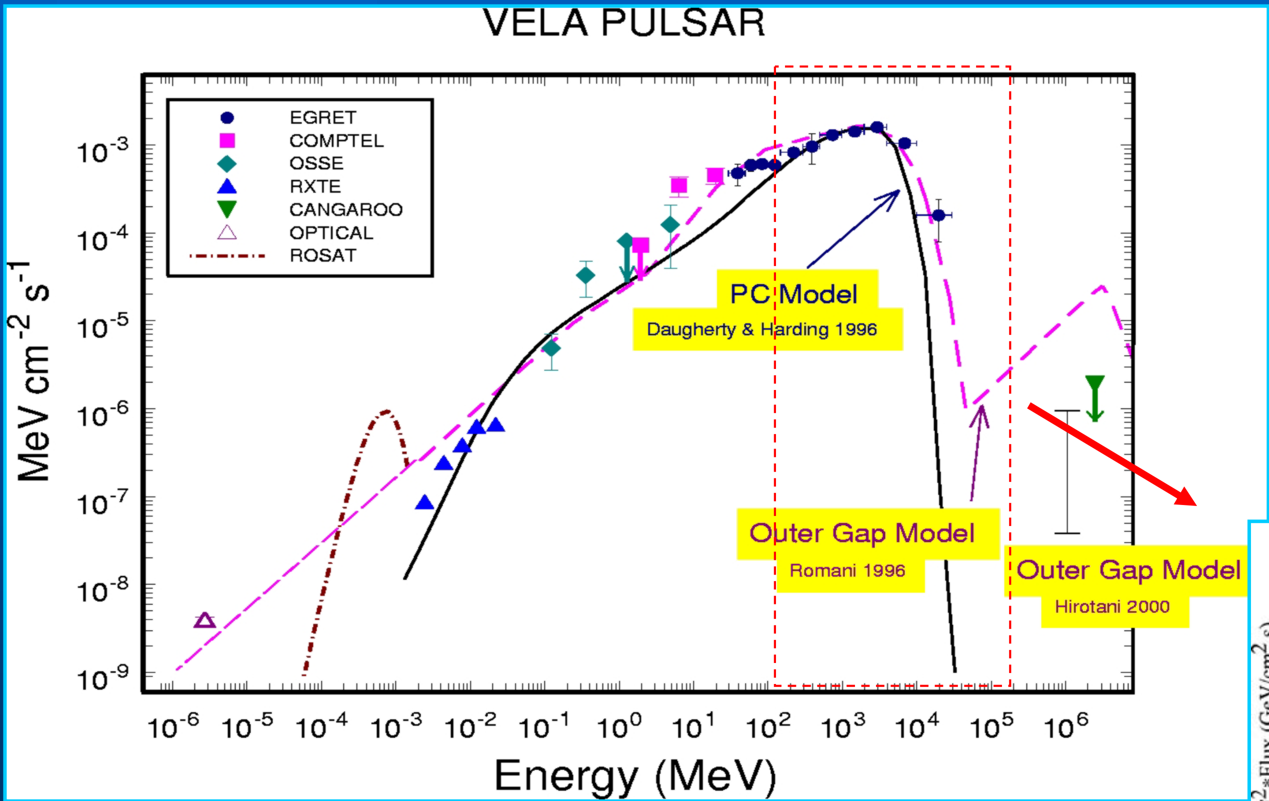
$$\gamma\gamma \rightarrow e^{+}e^{-}$$

(or IC photons with IR)
electrons emit synchrotron & curvature radiation

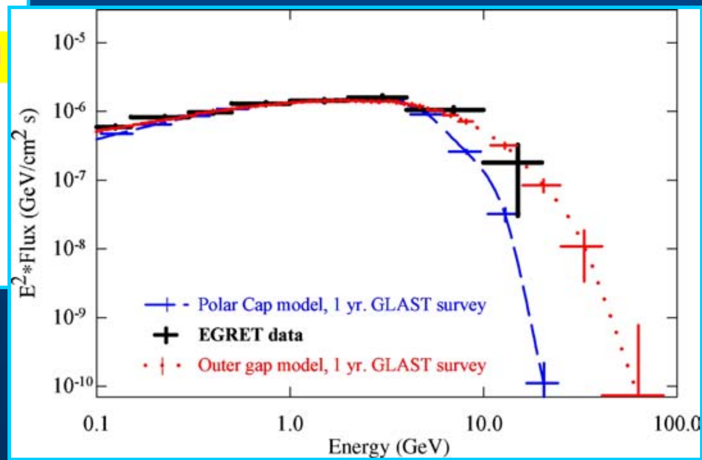
Radiation-reaction cutoff in primary particle spectrum ~ 10 GeV

Electrons may up scatter IR photons to TeV Gamma-rays !

Energy Spectra

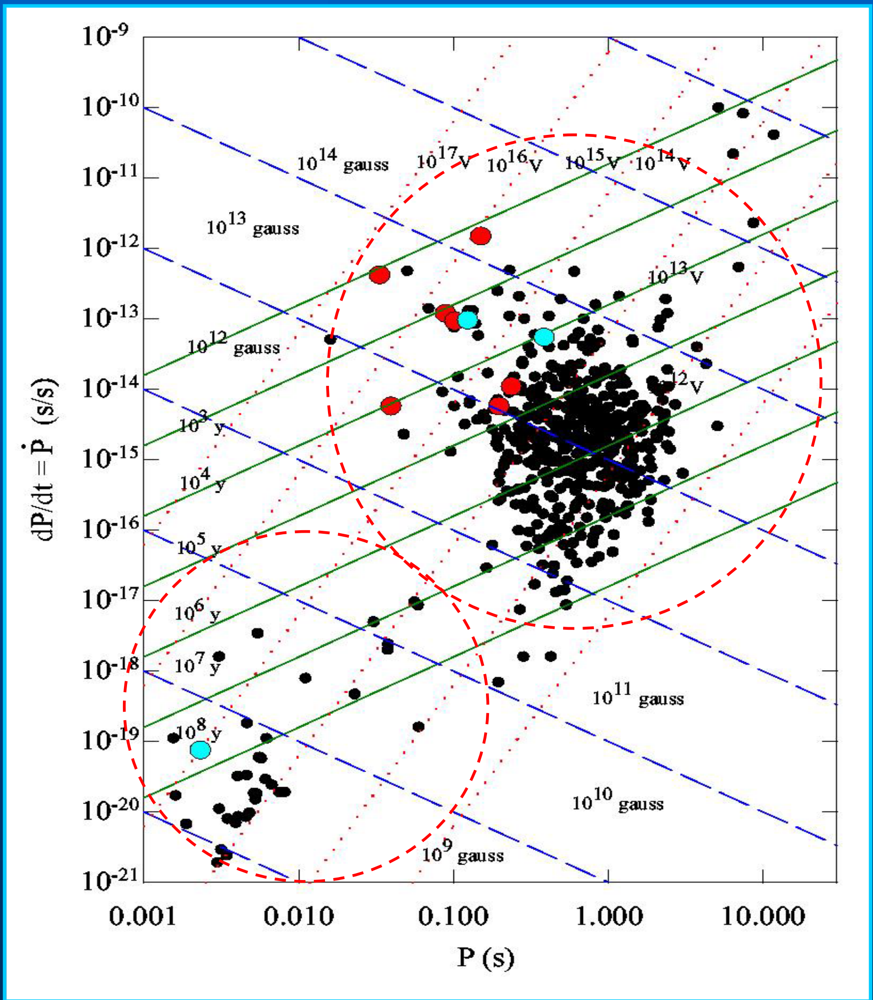


Harding, HDGS (2000)



Spectra are rather different above 10 GeV !

Sample of Radio Pulsars



Thompson (2000)

more than 1500 radio pulsars

~50 X-ray pulsars

7 gamma-ray pulsars

+3 candidates

← Normal pulsars

← Millisecond pulsars

EGRET Pulsars

Kanbach (2002)

Table of detections

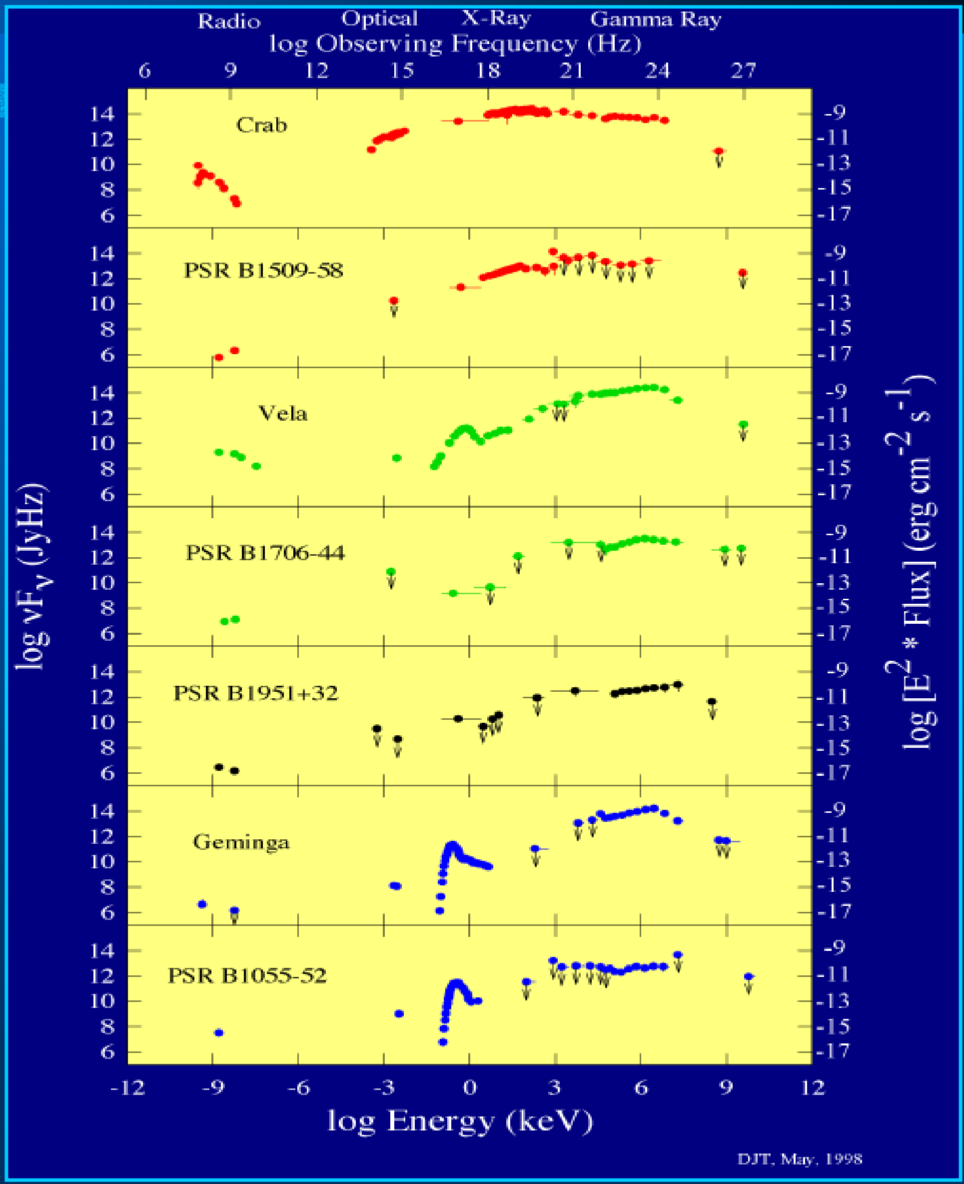
High-Energy Pulsars: Multiwavelength Detections

PSR	P (ms)	$\dot{E}/d^2$ rank	radio	opt	X_{low}	X_{hi}	γ_{low}	γ_{hi}
high confidence γ-ray detections								
B0531+21 (Crab)	33.4	1	P	P	P	P	P	P
B0833-45 (Vela)	89.3	2	P	P	P	P	P	P
J0633+1746 (Geminga)	237.1	3	P?	P?	P	P	?	P
B1706-44	102.5	4	P	?	D			P
B1509-58	150.7	5	P	D	P	P	P	
B1951+32	39.5	6	P		P		P	P
B1055-52	197.1	33	P	D	P		P	P
candidate γ-ray detections								
B0656+14	384.9	18	P	P?	P		?	?
B0355+54	156.4	36	P		D			?
B0631+10	287.7	53	P		D			?
B0144+59	196.3	120	P					?
candidate ms-PSR γ-ray detections								
J0218+4232	2.32	43	P		P			?
B1821-24	3.05	14	P		P			?
Likely PSR - γ-ray source positional coincidence								
B1046-58	123.7	8	P		D			D?
J1105-6107	63.2	21	P		D			D?
B1853+01	267.4	27	P					D?

P = pulsed detection, P? = low significance pulsation, D = unpulsed detection

Multi-wavelength Spectra of EGRET Pulsars

- Maximum of emission in the hard X- and Gamma-Ray range
- High Energy Spectral cutoffs



Very High Energy Gamma-rays from the Pulsars

Romani (1996)

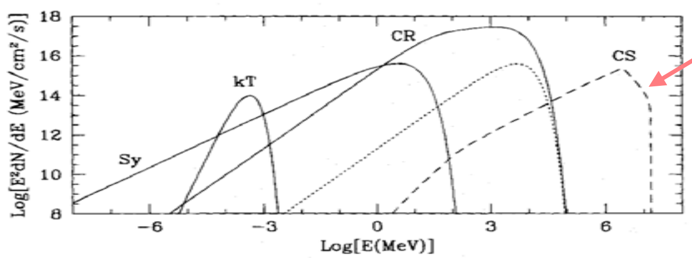
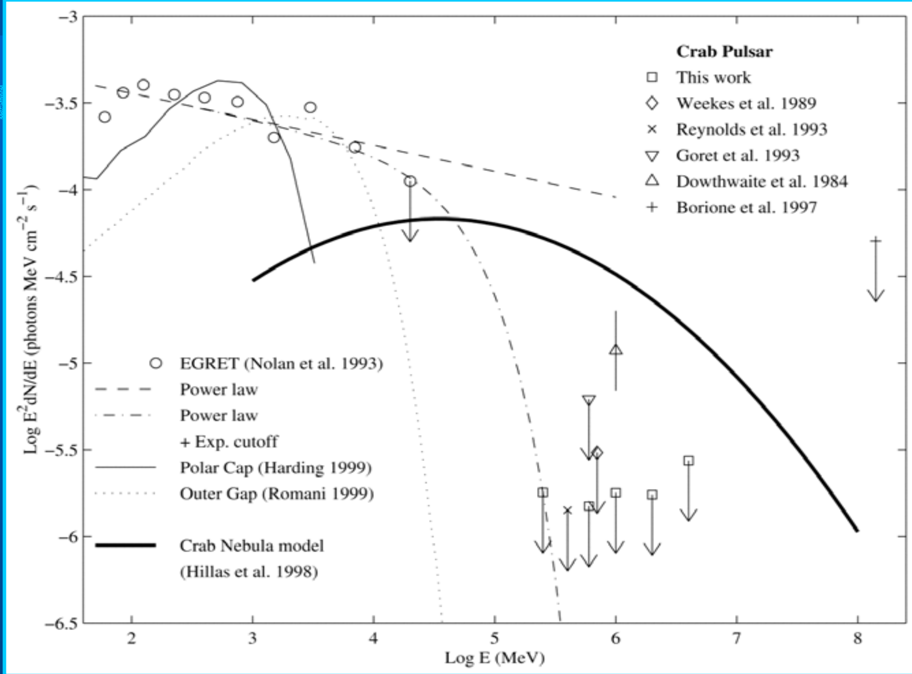
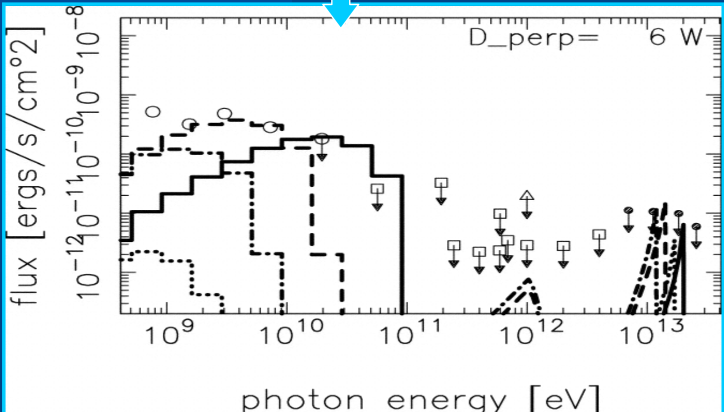


FIG. 5.—Characteristic phase-averaged spectrum for a young γ-ray pulsar ($B_{12} = 3$, $E_c = 3$ GeV). Solid lines show the curvature spectrum (CR), the synchrotron emission near r_i (Sy) and the thermal surface flux (kT) described in § 4. For comparison, the dotted curve gives the mono-energetic primary curvature spectrum with the same E_c as for CR. The dashed curve gives the TeV pulsed spectrum from Compton upscattering of the synchrotron spectrum on the primary $e^{\pm}$.



Lessard et al. (Whipple) (2000)



Hirotani & Shibata (2001)

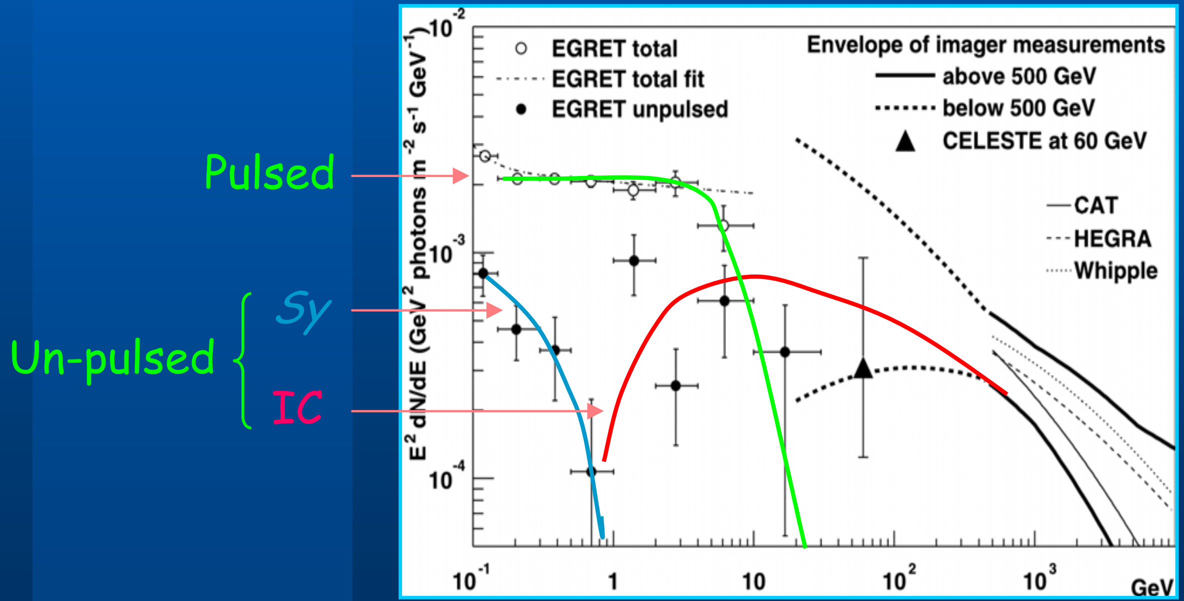
Aharonian et al. (HEGRA) A&A (1999)
Aharonian et al. (HEGRA) ApJ (2000)

Non-detection of pulsed emission with ground-based Cherenkov telescopes !

A Jigsaw Puzzle

No pulsed TeV Gamma-ray emission was detected from EGRET pulsars … but …
a few of them have shown DC TeV Gamma-ray emission (Crab,Vela, PSR 1706-44)

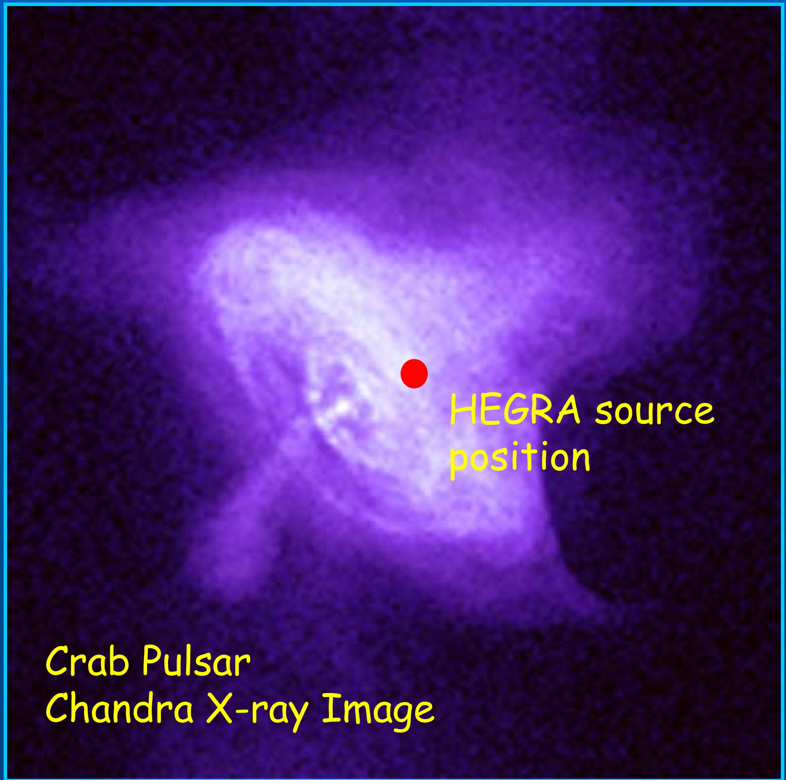
Where that emission comes from ? … from the X-ray nebula ?



de Narouis et al. ApJ (2002)

Future ground-based Cherenkov detectors must resolve this puzzle!

Pulsar-Nebulae

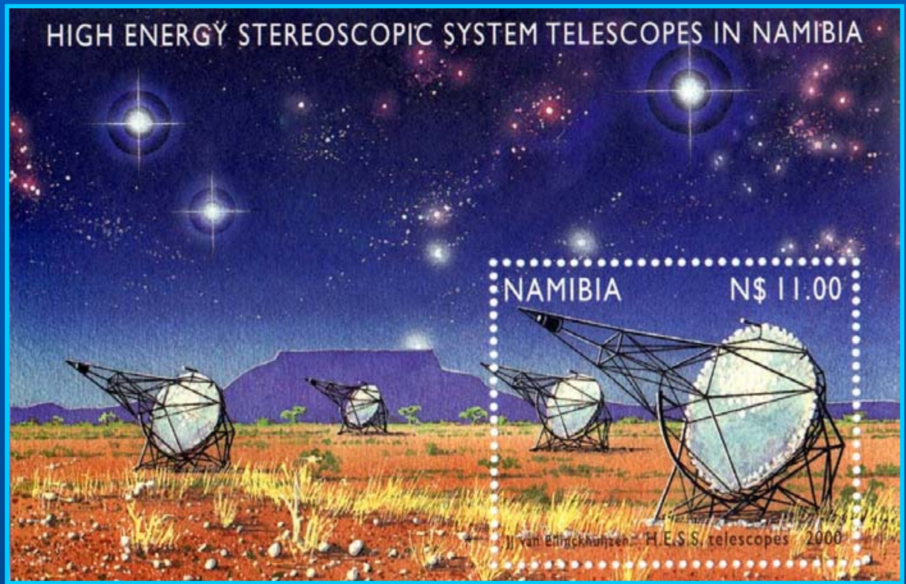


HEGRA measured Crab Nebulae energy spectrum from 300 GeV up to 20 TeV

HEGRA set an upper limit on extension of the source

Where does gamma-ray emission come from the Pulsar ? or extended Nebulae ?

H.E.S.S. Collaboration



MPI Kernphysik, Heidelberg
Humboldt Univ. Berlin
Ruhr-Univ. Bochum
Univ. Hamburg
Landessternwarte Heidelberg
Univ. Kiel
Ecole Polytechnique, Palaiseau
College de France, Paris
Univ. Paris VI-VII
CEA Saclay
CESR Toulouse
LAOG Grenoble
Paris Observatory
Durham Univ.
Dublin Inst. for Adv. Studies
Charles Univ., Prag
Yerewan Physics Inst.
Univ. Potchefstroom
Univ. of Namibia, Windhoek

Site of H.E.S.S.

Khomas Hochland, Namibia

- (22 deg South, 15 deg East)
- Farm Göllschau
- 1.5 driving hours from Windhoek

Advantages:

- Documented optical quality
- Mild climate
- Altitude ~1800 m
- Southern Hemisphere
- (complementary to VERITAS & MAGIC)
- Easy access & development

Telescope Mount

artistic drawing

Mirror area 108 sq.m

Space frame

- 60 tonn
- homogeneity & stiffness
- absolute pointing ~ 0.5 arc min
- telescope slews at 100 deg/min

Davies Cotton design

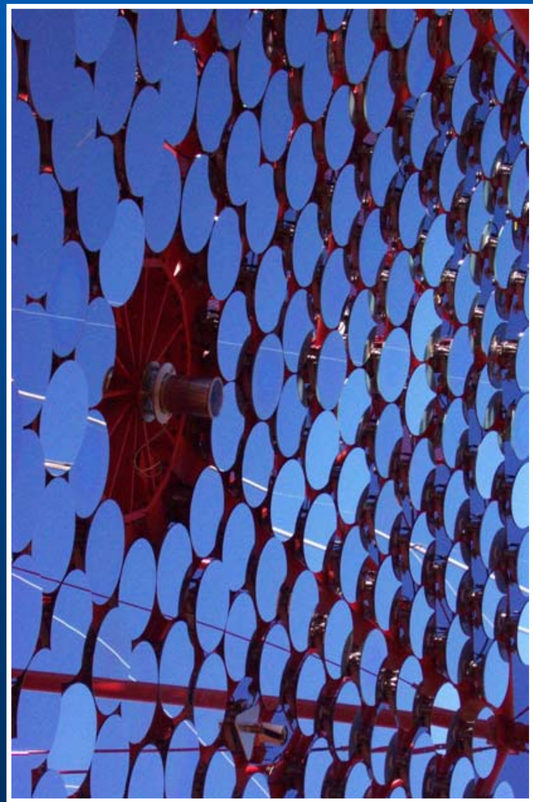
- 15 m focal length
- segmented

Mirror tiles

- 380 per telescope, d = 60 cm
- aluminized glass mirror
- 85% reflectivity

First H.E.S.S. telescope

… in operation



First camera is working …

Camera:

960 channels (pixels)

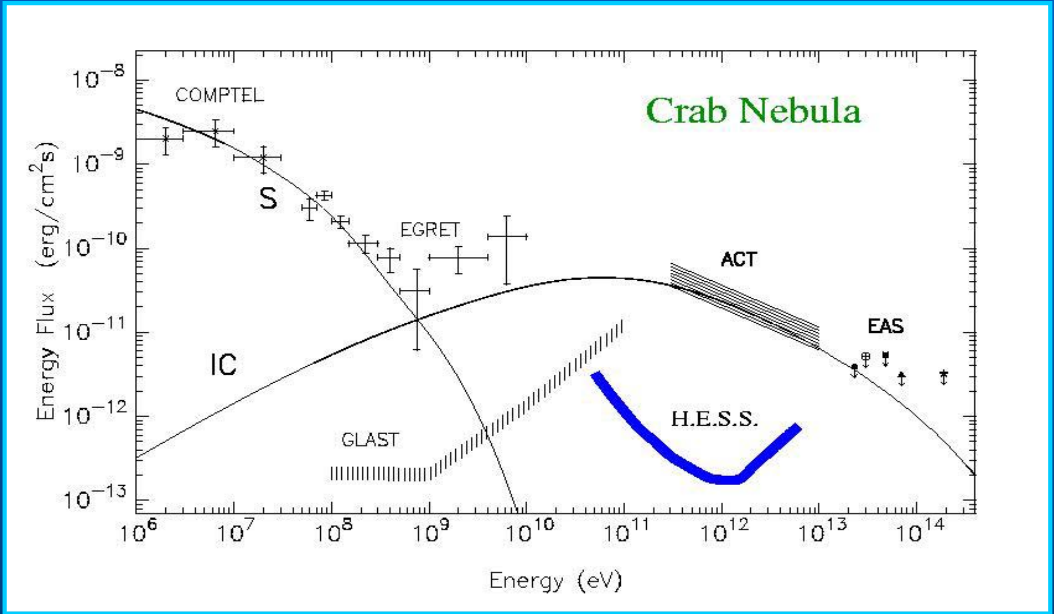
0.16 deg pixel size

5 deg field of view

View of H.E.S.S. Site

The steel structures of the four telescopes of Phase I of H.E.S.S. are complete.

Performance



Energy threshold: 50 GeV (detection)

100 GeV (spectroscopy)

Angular resolution: 0.1 deg (per event)

Energy resolution: 10-20% (per event)

H.E.S.S. flux sensitivity (Phase I)

New source populations at the 100 milli-Crab level in the TeV energy range !

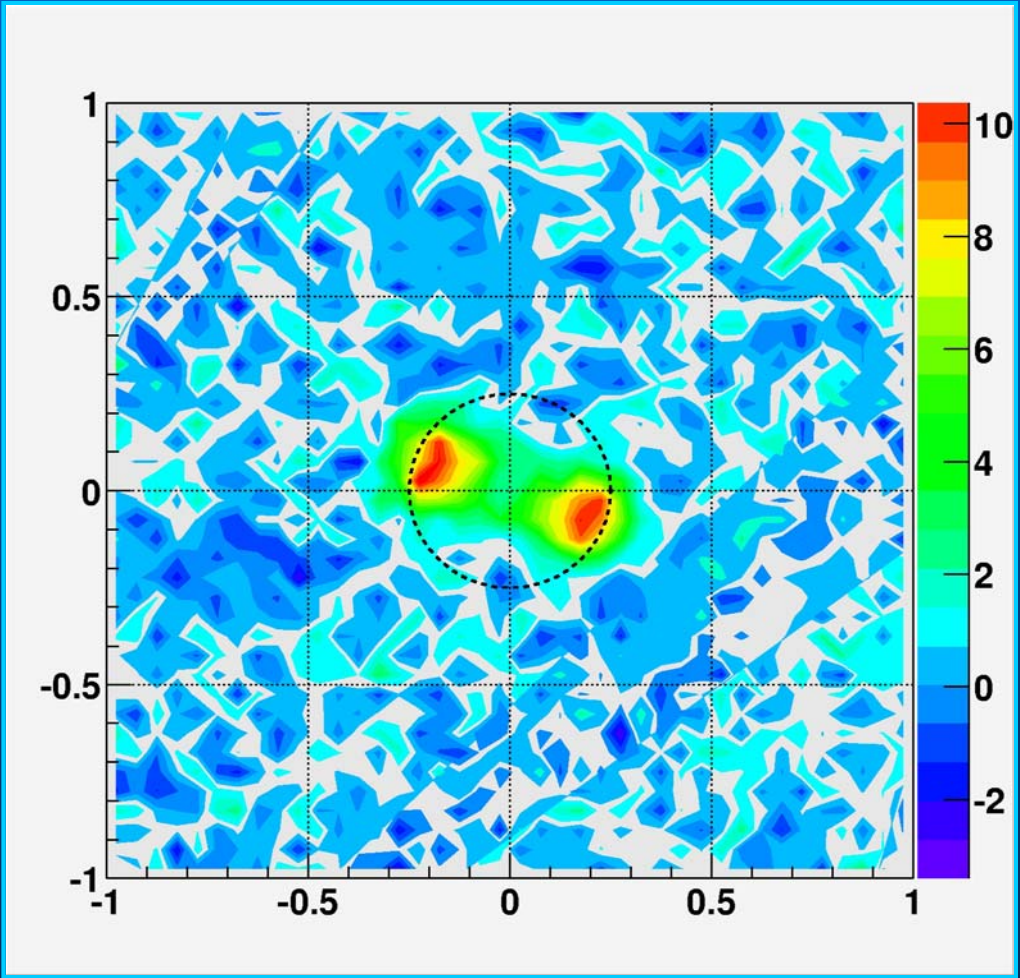
Sensitivity: F(>100 GeV) = $10^{-11}\ ph/cm^2\,s$

Min. energy flux: $\sim 10^{-12}\ ergs/cm^2\,s\ \ at\ 100\,GeV$

$\sim 10^{-13}\ ergs/cm^2\,s\ \ at\ 1\,TeV$

in 50 hrs of observations

Angular Resolution



SN 1006

Simulation of the H.E.S.S. (phase I) response after 15 hrs of observations

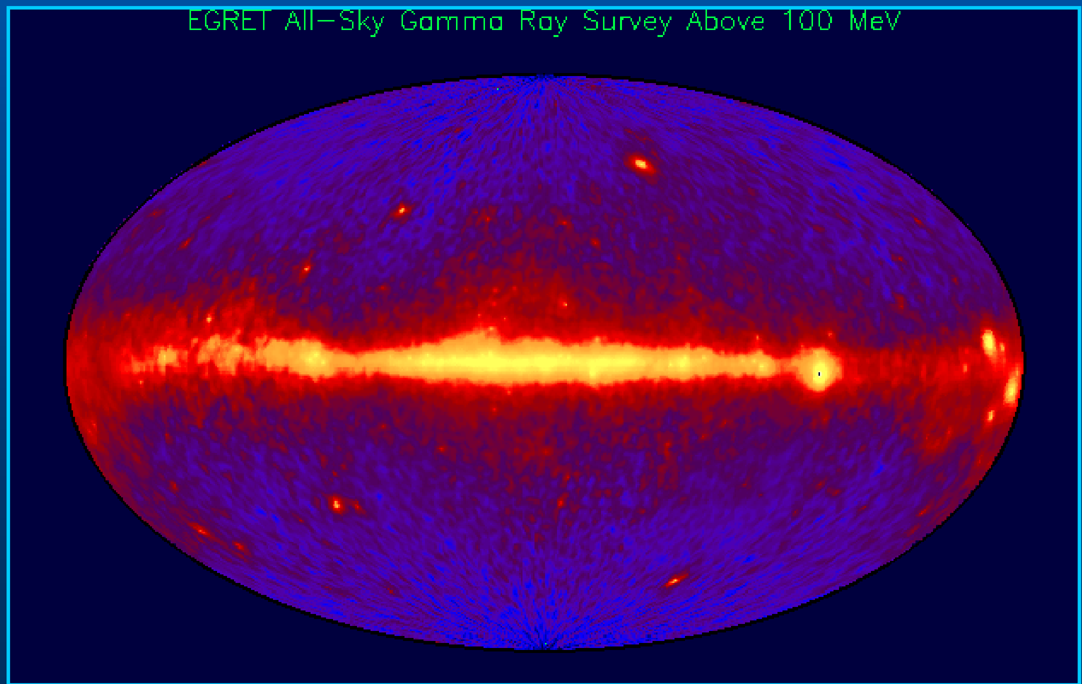
Double Pole Model

Völk, H.J. et al (2002)

Science Motivation of H.E.S.S.

“A comprehensive study of non-thermal phenomena in the universe using VHE gamma rays as a diagnostic tool, with emphasis on the precise spatial and spectral mapping of sources”

Example:
EGRET sky map



Non-thermal Universe

With localized Gamma-Ray “Sources”

- Pulsars, Pulsar-Nebulae
- Supernova Remnants (SNR)
- Normal/Starburst Galaxies
- Radio Galaxies, Quasars (AGN)
- Galaxy Clusters: IC Gas
- Intergalactic Pair Halos

Plus: Dark Matter annihilation regions ?

(Galactic Center …)

Science Hopes for H.E.S.S.

Major Physics Questions:

- Pulsars/Pulsar-Nebulae: Stable structures ? B-Field/Escape ?
- Supernova Remnants: Sources of the nuclear Cosmic Rays below the knee ?
- Normal/Starburst Galaxies: Cosmic Rays in the Universe ?
- Radio Galaxies, Quasars (AGN): Nature of Jet emission ? Intergalactic Gamma-ray absorption ?
- Galaxy Clusters: Non-thermal history of cluster formation ?
- Intergalactic Pair Halos: Evolution of EBL in Universe ?
- Dark Matter annihilation signatures (Galactic center …): indirect detection of Dark Matter particles (Neutralinos) ?

Infrastructure

Control room

Dormitory

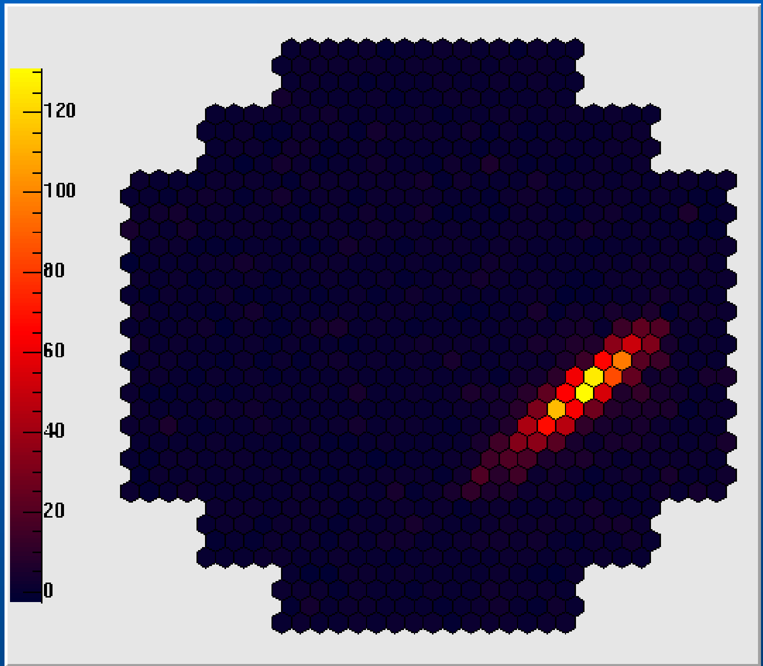
First Light Workshop

September 2-4, 2002,
Windhoek, Namibia

Inauguration Meeting on H.E.S.S. Site

Open Science Meeting in Windhoek

First Data



Event display

Data rate: 220 - 270 Hz

Energy threshold: ~ 180 GeV

Current targets:

SN 1006

RXJ 1713-3946

PSR 1706-44

Crab

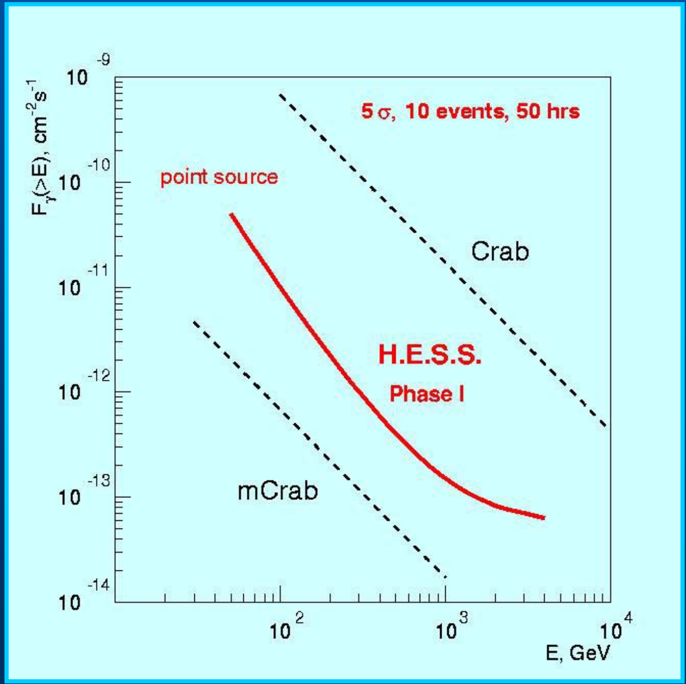
PKS 2155-304

...

H.E.S.S.-Background

- Successful use of stereoscopic concept by HEGRA
- HiRes Camera and optics developed by CAT and HEGRA
- Long term scientific expertise in collaborating groups
- Participation of leading astrophysics groups

H.E.S.S. is an instrument of the next generation for VHE Gamma-ray astronomy !



All about H.E.S.S.

http://www-hfm.mpi-hd.mpg.de/HESS/HESS.html

Targets #1: EGRET Pulsars

Spectrum fit: $dN_\gamma / dE = K(E/E_n)^{-g} \exp(-(E/E_0)^b)$ $K(cm^{-2}s^{-1}GeV^{-1})$ at 1 GeV

Array of 4 IACTs (H.E.S.S. Phase I)
Standard parameters plus
topological trigger mode

Lucarelli, Konopelko, et al (HEGRA) (2002)

Detection capability:

Table 1. Gamma-ray spectral parameters above 1 GeV and corresponding H.E.S.S. rates and observation time for detection. Spectral references from Macomb & Gehrels (1999).

Object	k ($\times 10^{-8}$) ($cm^{-2}s^{-1}GeV^{-1}$)	g	E_o (GeV)	b	$F(>1$ GeV$)$ ($cm^{-2}s^{-1}$)	R_p ($hour^{-1}$)	T (10-hour days)
Crab	24.0	2.08	30	2	22	100	3
Vela	138	1.62	8.0	1.7	148	8	400
Geminga	73.0	1.42	5.0	2.2	76	$\ll 1$	-
PSR B1951+32	3.80	1.74	40	2	4.9	180	1
PSR B1055-52	4.00	1.80	20	2	4.5	8	420
PSR B1706-44	20.5	2.10	40	2	20	240	1
PSR J2229+61	4.8	2.24	40	2	3.9	32	25
PSR J1420-60	6.9	2.02	40	2	6.9	110	2
PSR J1837-06	5.5	1.82	40	2	6.7	190	1

de Jager, Konopelko, Raubenheimer, Visser (2001)

Target #2: Millisecond Pulsars

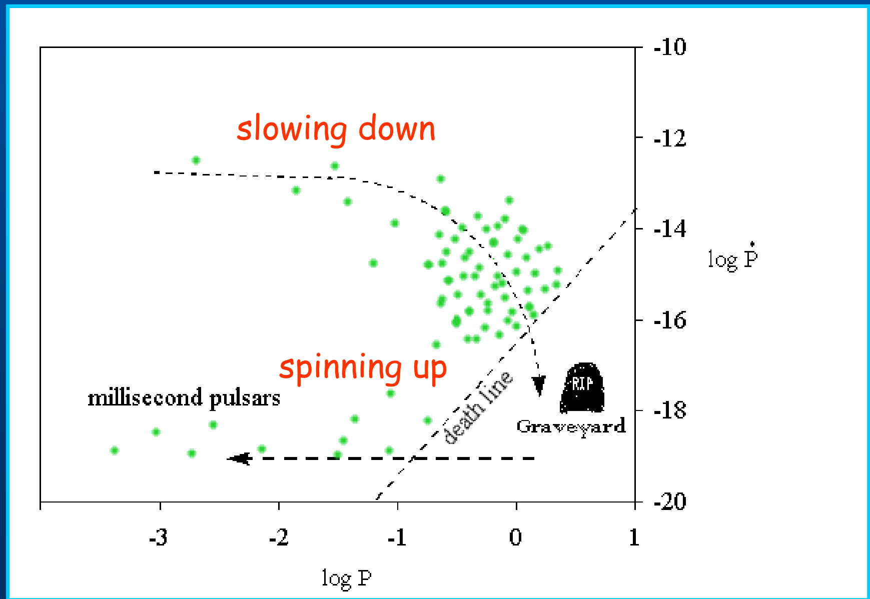
Extremely short periods: $1-10\ ms$

First millisecond pulsar – PSR 1937+21   Backer et al. Nature (1982)

$P = 1.6\, ms$ $\dot{P} = 10^{-19}$

Youngest Crab Pulsar is 1000 years old with $P = 33\ ms$

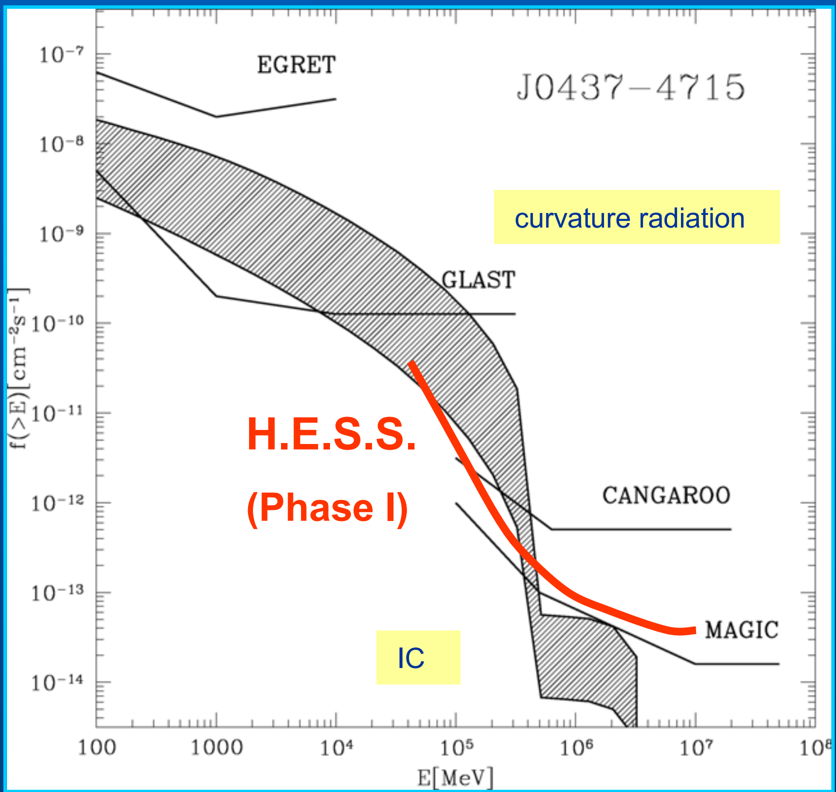
Millisecond pulsars must be spun up by the external mechanisms, e.g. accretion from the companion star



Usov, Nature (1983)

Very low magnetic field $B \cong 5\times10^{8}\,G$ inferred from P and $\dot{P}$

Maximum radiation of the millisecond pulsars is at $\sim 10^{11}\,eV$



Bulik, Rudak, Dyks (2000)

Detailed calculations in Polar Cap Model

$P = 5.75\,ms, B_{pc} = 7.4\times10^{8}\,G, d = 140\,pc$

Camilo et al (1994)

Millisecond Pulsar J0437-4715 is a good candidate for the future observations !

Target #3: Unidentified EGRET Sources

TABLE 2

POSITIONAL COINCIDENCES BETWEEN UNIDENTIFIED 3EG SOURCES AND PARKES PULSARS

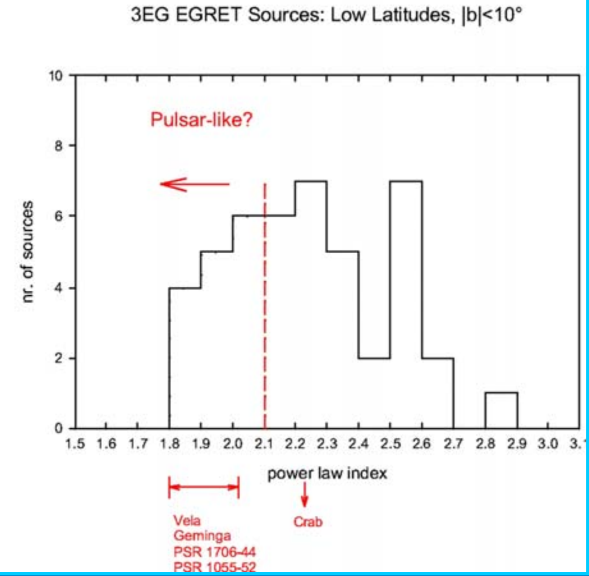
3EG Source	Note	I	PSR J	Case	SNRs	Reference	$\dot{E}/d^2$
J1013−5915	C, em	1.6	1016−5857	1	G284.3−1.8	1	2.9×10^{35}
	C, em	1.6	1013−5934	2			2.0×10^{30}
J1014−5705	C, em	1.4	1015−5719	3			3.4×10^{34}
J1410−6147	C	1.2	1412−6145	4	G312.4−0.4		1.4×10^{33}
	C	1.2	1413−6141	5			1.6×10^{33}
J1420−6038	C	2.1	1420−6048	6		2	1.7×10^{35}
J1639−4702	C, em	1.9	1637−4642	7	G337.8−0.1; G338.1+0.4; G338.3+0.0		1.9×10^{34}
	C, em	1.9	1640−4648	8			1.5×10^{32}
	C, em	1.9	1637−4721	9			3.1×10^{30}
J1714−3857	C, em	2.1	1713−3844	10	G348.5+0.0; G348.5+0.1; G347.3−0.5	3	4.0×10^{31}
	C, em	2.1	1715−3903	11		3	3.0×10^{33}
J1837−0423	C	5.4	1838−0453	12	G27.8+0.6		1.2×10^{33}
J1837−0606	C, em	2.4	1837−0559	13			6.5×10^{32}
	C, em	2.4	1837−0604	14		2	5.2×10^{34}

NOTE.—A number is assigned to each pair for ease of reference. SNRs contained in Green's 2000 catalog (available at http://www.mrao.cam.ac.uk/surveys/snrs) coinciding with the EGRET sources are noted (see Torres et al. 2001a). Only in cases 4, 5, and 12 do the pulsars also coincide with the SNRs listed. "C" and "em" refer to the γ-ray sources: source confusion exists and sources are possibly extended or multiple, respectively (Hartman et al. 1999). I is the variability index as in Torres et al. (2001b, 2001c), where $I > 5$ (<2) represents a source whose flux presents variability levels at least 8 σ (less than 2 σ) above those displayed by confirmed pulsars. Pulsar "spin-down flux" $\dot{E}/d^2$ is in units of ergs s^{-1} kpc^{-2}.

REFERENCES.—(1) Camilo et al. 2001; (2) D'Amico et al. 2001; (3) Butt et al. 2001.

There is a good number of coincidences between Unidentified 3EG sources & Parkers Pulsars !

Spectra of unidentified galactic sources



About 1/3 of the unidentified sources have hard ‚pulsarlike' spectra

Kanbach (2002)

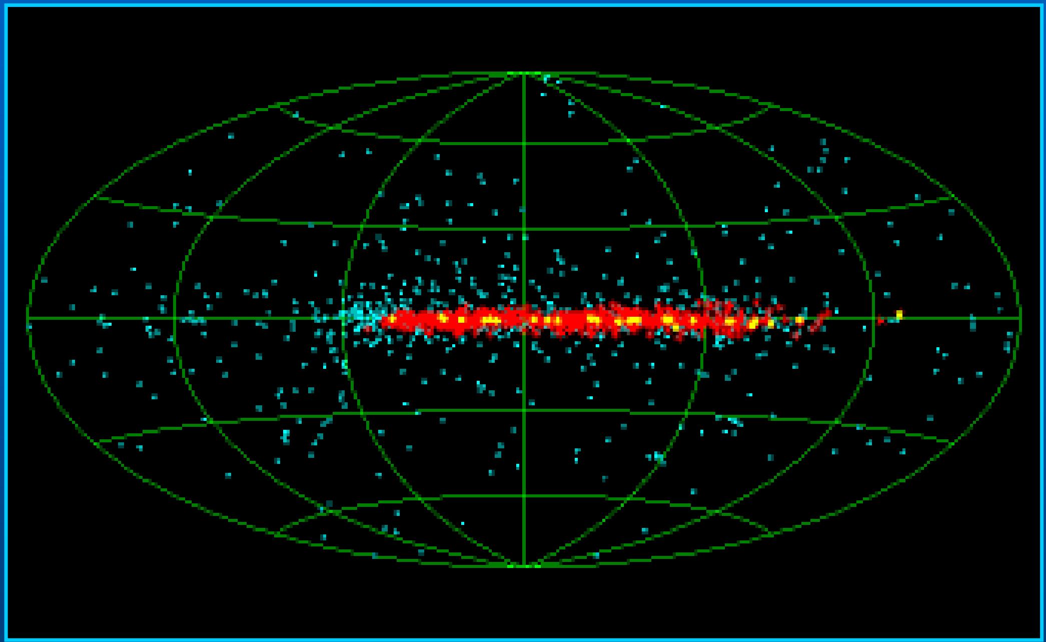
Table 1. Gamma-ray spectral parameters above 1 GeV and corresponding H.E.S.S. rates and observation time for detection. Spectral references from Macomb & Gehrels (1999).

Object	k ($\times 10^{-8}$) ($cm^{-2}s^{-1}GeV^{-1}$)	g	E_o (GeV)	b	$F(>1$ GeV$)$ ($cm^{-2}s^{-1}$)	R_p ($hour^{-1}$)	T (10-hour days)
PSR J2229+61	4.8	2.24	40	2	3.9	32	25
PSR J1420-60	6.9	2.02	40	2	6.9	110	2
PSR J1837-06	5.5	1.82	40	2	6.7	190	1

de Jager, Konopelko, Raubenheimer, Visser (2001)

Young Pulsars 3EG associations do not evidently show a spectral cutoff, and could be easy seen with H.E.S.S. !

Target #4: Parkes Pulsars



- all known radio pulsars
- Parkes sources
- coincidences with EGRET unidentified sources

D'Amico, Gamma-Ray Astrophysics Symposium, Baltimor (2001)

30 of new young radio pulsars correspond in position to unidentified EGRET gamma-ray sources

Many of the unidentified EGRET sources could be Pulsars !

Summary

What H.E.S.S. can do ?

- First Pulsar Detection at Very High Energies from the Ground !!!
- Precise Spectral Measurements of DC & Pulsed Components (above ~10 GeV)
- Constrains on Polar Cap & Outer Gap Models (energy cut-offs, light curve)
- Prove (disprove) millisecond Pulsars as the Sources of High Energy Gamma-rays
- Studies on Physics of Pulsar/Plerions
- *etc*