VHE Pulsars at Very High Energies

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EGRET Era (< 2008) GRO: April 5th 1C991- June 4th 2000

- First discovery in 1967 : 1919+21 [Hewish & Bell 1967]
- ATNF catalog > 2900 radio pulsars
- Crab in soft/hard γ-rays : only 2 yrs after its discovery [Hillier et al. 1970] /[Albats et al. 1972]
- GeV γ-rays prior to Fermi : Egret/CGRO (1990's) : 7 pulsars
- X-rays : ~100 pulsars mostly thermal
- Optical : ~10 pulsars, very faint Mv(Crab) =16.5 Mv(Vela) = 23.5 !
- Most of energy in GeV range
- Bump in UV-X-rays for 3 pulsars



[Thompson et al. 1999]

EGRET Era (< 2008) GRO: April 5th 1991- June 4th 2000

- 7 pulsars detected
- Polar Cap : super-exponential cut-off
- Outer/slot gaps : exponential cut-off
- Data in [1-10] GeV on brightest pulsars : —> not constraining





HESS searches for VHE pulsations

Data 2002-2005 [HESS collab. 2007]

• Constraints on OG [Dyks & Rudak]+ IC models [Hirotani et al., 2001, 2003], [Takata et al. 2006], ...



HESS searches for VHE pulsations

Data 2002-2005 [HESS collab. 2007]



- 11 "young" isolated pulsars selected
- Except B1259-63 with a companion
- $\dot{E}/d^2 > 10^{35} \, {\rm erg/cm2/s}$
- (Characteristic) Ages range from 1.24 to 332 kyrs
- ~350 h of total observing time
- No significant excess found

Pulsar	Low energy cuts						Standard cuts					
PSR	Non	P_{χ^2}	P_H	$P_{Z_{1}^{2}}$	$P_{Z_{2}^{2}}$	P_K	Non	P_{χ^2}	P_H	$P_{Z_{1}^{2}}$	$P_{Z_{2}^{2}}$	P_K
B0531+21	8095	0.99	0.84	0.81	0.94	0.97	10622	0.51	0.56	0.63	0.25	0.66
B0833-45	7480	0.52	0.87	0.85	0.37	0.82	1156	0.79	0.92	0.90	0.98	0.88
B1259-63	16176	0.78	0.92	0.90	0.65	0.71	4535	0.29	0.25	0.18	0.46	0.23
J1420-6048	2228	0.0093	0.0031	0.072	0.007	0.0049	968	0.67	0.60	0.53	0.53	0.62
B1509-58	12481	0.37	0.81	0.77	0.70	0.89	4308	0.048	0.055	0.027	0.11	0.04
J1524-5625	2498	0.78	0.43	0.35	0.43	0.39	745	0.87	0.79	0.75	0.96	0.97
B1706-44*	-	-	-	-	-	-	391	0.02	0.82	0.78	0.85	-
J1826-1334	14497	0.71	0.46	0.38	0.57	0.62	4016	0.46	0.42	0.34	0.34	0.42
J1747-2958**	23482	0.65	0.98	0.97	0.82	0.95	6340	0.62	0.62	0.92	0.99	0.96
J1801-2451**	3230	0.035	0.22	0.15	0.42	0.21	723	0.50	0.15	0.094	0.24	0.32

* Subject to analysis limitations (archival data, see text).

** Valid pulsar timing information was not available for all data within the H.E.S.S. data set.

Crab: MAGIC 2008 ~25 GeV [Aliu et al. 2008]

- Sept 2008 (17th)
 - Detection of a signal > 25 GeV !
 - 23 hours, 8500 events at 6.4 s.d. from peaks P1 and P2
 - P2 > 60 GeV : 3.4 s.d.

- Spectral energy distribution
- Exp-cutoff E pushed to 17.7 GeV
- Polar Cap models disfavored
- But uncertainties on energy scale forbid strong conclusions



Fermi-LAT Era (>2008)

Launch of Fermi : June 11th 2008

- As soon as September 2009:
- Super exponential cutoff excluded !
- Brightest pulsars (Crab, Vela) : even subexponential cut-off
- Cut-offs in a narrow band E_cut ~1-5 GeV
- Taken as evidence for CR
- Reasonable values for ρ_cand E_{||} indeed predict
 E_cut in this range
- As such no hope for VHE emission, except:
 - Tails of exp-cut off in the <50 GeV range
 - New component e.g. IC à la Hirotani & Shibata OG model, but already severely constrained by HESS...

Fermi-LAT > 1 GeV sky

11 years of data

- 3PC in preparation ~255 pulsars
- 136 Young or Middle-aged
- 73 Radio-loud γ-ray (29%)
- 63 Radio-quiet γ-ray (25%)
- 119 γ-ray MSPs : 25 Isolated, 94 Binary (47%)
- 36 Black Widows (27) and Redbacks (9)
 - Public list of LAT detected pulsars : <u>https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars</u>

Courtesy David Smith

Fermi-LAT Era (>2008) Launch of Fermi : June 11th 2008

-60

Crab: VERITAS 2011 100-400 GeV [Aliu et al. 2011]

- Detection of a signal in the 100-400 GeV !
- 107 hours, 1211 events at 6.0 s.d. from peaks P1 and P2
- Confirmed by MAGIC

- Spectral energy distribution
- First case of departure from exp-cutoff?
- Broken power-law :
 - Stand alone fit : $\Gamma = -3.8 \pm 0.5$
 - Combined Fermi-VERITAS fit :

 $\Gamma 1 = -1.96 \pm 0.02$ $\Gamma 2 = -3.52 \pm 0.04$ Assuming same component

Crab : MAGIC 2016 70 GeV-~1 TeV [Ansoldi et al. 2016]

- Extension to ~ 1 TeV
- 320 hours!
- 100-400 GeV
- P1: 1252 events at 2.8 s.d.
- P2:2537 events at 5.6.s.d.
- >400 GeV
 - P1 : 188 events at 2.2σ
 - P2 : 544 events at 6.0σ
- Spectral energy distribution

P1 :	$\Gamma = -3.2 \pm 0.4$
P2 :	Γ = -2.9 ±0.2
Combined	Fermi-MAGIC fit :
P1 :	Γ = -3.5 ±0.1
P2 :	Γ = -3.0 ±0.1

- In continuation of Fermi-LAT?
- Same component?!
- If so : departure from exp-cutoff confirmed
- Traditional Curvature radiation interpretation seriously challenged

H.E.S.S. Detection of the Vela PSR

Vela Pulsar detection with H.E.S.S.-II (monoscopic)

[Djannati-Ataï et al. 2016]

- 2012 upgrade of H.E.S.S.: Addition of CT5, Ø28m (eq), 600m²
- Vela pulsar: among first targets
- 40.3 h of data (2013-2015)
- To achieve the lowest threshold
 - Data kept only from CT5
 - Dedicated monoscopic reconstruction
 pipeline
- Signal of >15000 events with a significance > 15σ from the second peak P2
- Down to 10 GeV !
- P1, P3 show some excess but are not significant : expected from Fermi-LAT
- P1/P2 decreases with increasing E

Instrument	Energy range	$\langle E_{\rm true} \rangle$	$\phi_{ m P2}$	$\sigma_{ m L}$	$\sigma_{ m T}$	
	(GeV)	(GeV)	(phase units)	(phase units)	(phase units)	
<i>Fermi-</i> LAT	1-3	1.7	0.5648 ± 0.0001	0.0327 ± 0.0002	0.0080 ± 0.00008	
<i>Fermi-</i> LAT	3-10	4.8	0.5653 ± 0.0002	0.0323 ± 0.0004	0.0056 ± 0.0001	
<i>Fermi-</i> LAT	10-20	13	0.5650 ± 0.0005	0.025 ± 0.001	0.0038 ± 0.0003	
<i>Fermi-</i> LAT	>20	28	0.565 ± 0.001	0.017 ± 0.002	0.0029 ± 0.0008	
H.E.S.S. II	~ 10-33	19	$0.564^{+0.001}_{-0.001}$	$0.019^{+0.003}_{-0.002}$	$0.006^{+0.001}_{-0.001}$	
H.E.S.S. II	~ 20-80	42	$0.5697^{+0.0005}_{-0.0011}$	$0.031^{+0.006}_{-0.005}$	$0.0007\substack{+0.0015\\-0.0007}$	
H.E.S.S. II	~ 10-80	31	$0.5684^{+0.0007}_{-0.0013}$	$0.027\substack{+0.003 \\ -0.003}$	$0.002\substack{+0.0014\\-0.0008}$	

Spectral Energy Distribution

- H.E.S.S. II spectrum of P2: power-law fit in [10-110] GeV
- Fermi-LAT power-law fit >10 GeV: perfect agreement
- Bound on energy scales: $(E_{\text{LAT}} - E_{\text{HESS}})/E_{\text{LAT}} \leq 8\%$
- Last significant bin: <E>=80 GeV, 909 events, 3.3 σ $_{10^{\text{-13}}}$
- Fermi-LAT: > 10 GeV evidence for curvature at 3.3 σ
- Variation of the power-law index as a function of energy threshold
- The curved nature of P2 is also favoured by the H.E.S.S.II measurement at > 3.0 σ
- This is at variance from the Crab pulsar case

Instrument	Threshold	Γ
H.E.S.S. II	~ 10 GeV	4.06 ± 0.16
Fermi-LAT	10 GeV	4.10 ± 0.08
H.E.S.S. II	~ 20 GeV	5.05 ± 0.25
Fermi-LAT	10 GeV	4.80 ± 0.30

3 to > 7 TeV detection of the Vela Pulsar with H.E.S.S !

[Djannati-Ataï et al. 2017]

- Data from 2004-2016 observations
- 80 hours in stereoscopic mode: at least 2 telescopes among CT1-CT4
- Signal detected in the 3 to beyond 7 TeV from P2
- Stay tuned for details in the forthcoming paper

0.4

Phase

2.5

Geminga : MAGIC 2019-2020

[Lopez, M. et al. 2019, Acciari, V.A. et al. 2020]

- Exposure = 80 hours (with dedicated low-energy trigge
- Detection in 15-80 GeV

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- Exposure = 80 hours (with dedicated low-energy trigger)
- Detection in 15-80 GeV

- Power-law joint-fit to Fermi-LAT and MAGIC data yield a steep spectral index ~5.2
- Curvature > 10 GeV not
 significantly preferred vs Power law (1.3σ only)
- Not yet possible to either confirm or rule out a powerlaw behaviour of the spectrum

Detection of PSR B1706-44 with H.E.S.S

[Spir-Jacob, M., A.D-A et al. 2019]

- Vela-like : Edot=3.4x10³⁶ erg/s p= 102 ms, 17 kyrs @ 2.3 kpc except:
 - 3rd brightest, but ~8 times more distant
 - Light curve
- Data from 2013-2015 observations
- 42 hours in monoscopic mode with CT5
- Detected in the 10-80 GeV range

- On=[0.25-0.55] & Off = [0.6-0.2] regions based on Fermi-LAT > 15 GeV
- Pulsed excess = 7171 events
- Significance level = 4.74σ
- Maximum likelihood ratio test based on Fermi-laT derived PDF:
- Pulsed excess = 8139 events
- Significance level = 4.6σ

PSR B1706-44 with H.E.S.S Phase-resolved spectrum

HESS >10 GeV 3.76 ± 0.36 (4.3 ± 0.9)x10⁻⁸

- Clearly the brightest pulsars in 2PC
- No other distinguishing parameter

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Interpretation & Models HE + VHE

Acceleration/emission Geometries

- Polar caps 😑
- Slot gaps
- Outer gaps
- LC to Y point
- Wind zone : inside current sheet (CS)

Accelerating force

- MHD force-free : no acceleration!
- Parallel E_{\parallel} in gaps
- Reconnection in CS

Emission mechanisms

GeV component

- Curvature, Synchrotron (Cyclotron) Synchro-Curvature?
- Within magnetosphere, close to LC or far in the CS? Reconnection in CS

TeV component

- Inverse Compton(IC)
 - SSC (Synchrotron Self Compton)?
 - IC on soft (opt- IR-far IR), X-rays?
- Within magnetosphere, close to LC or far in the CS?

Crab Emission models : E_{\parallel}

CSC model for Crab : Inverse Compton [Lyutikov 13']

Dual annular gap [Du et al 12']

SSC model for Crab [Kalapotharakos & Harding 15']

Crab Emission models: wind, E_{\parallel} + unknown

Cold wind [Aharonian et al. 2012]

- Acceleration and emission zones well beyond the Light Cylinder
- Abrupt acceleration ($\Gamma_w \sim 10^5 10^6$) unknown mechanism
- Inverse Compton scattering off the lower energy pulsed emission (IR, X-rays)
- Implies 2 components
- 20-50 R_LC fits the 80-400 GeV (red)
- Did not survive to the extension to 1 TeV (low energies not reproduced (see Bogovalov et al 2017).
- Note: phase-averaged fit

c: Gamma-Ray Signal from Pulsar Wind Accelerated between $20R_L$ and $50R_L$

Crab Emission models : wind, reconnection

Striped wind [Arkas & Dubus 2012, Mochol & Pétri 2015, Mochol 2017]

- Particle energisation within current sheet and close to the Light Cylinder
- GeV emission through synchrotron radiation in the current sheet
- A synchrotron Self-Compton component is predicted to extend beyond 1 TeV
- Young/powerful pulsars like Crab : $\Gamma_w < 100$
- Vela-like : $\Gamma_w < 50$

- Note : phase averaged fit
- Some light curve properties, e.g. thinning of peak widths with energy, remain to be reproduced
- Did survive to the extension to 1 TeV

Vela VHE emission : A second component: Inverse Compton!

- Cheng, Ho & Ruderman (1986) :
 - IC: general considerations
- Romani 1996: IC: OG primary e⁻ + IR
- Hirotani & Shibata (2001), IC: OG primary e⁻ + IR
- Aharonian & Bogovalov (2003), IC: OG primary e⁻ + IR

Vela VHE emission : A second component

- Mochol & Pétri (2015): SSC:
 - Striped wind/ current sheet;
 → No component expected for Vela
- Harding & Kalapathorakos (2015):
 - SSC from primaries and pairs inside/outside LC
 → No component expected for Vela
- Rudak & Dyks (2017): IC: OG primary e⁻ + optical/IR
 - → phase resolved

Harding & Kalapathorakos (2015)

Vela VHE emission :

A second component

- Harding (2018) : IC component SG primary accel.
 by E_{II} to beyond LC + optical/IR
- Inside and outside LC, different electric field intensities
- GeV: (synchro-)curvature,
- Very very faint VHE component predicted (2015)
- VHE: IC on opt-IR from poles
- IC Flux, index, depends on target assumptions
- Fit to data points is difficult

[Hakobyan et al. 19]

 $E_{
m cutoff} \propto \gamma_{
m max}^2 B_{
m LC} \propto B_{
m LC}^3 P^2$

observed flux

Towards a new era with CTA?

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Towards a new era with CTA

- Out of > 250 Fermi-LAT pulsars expect roughly a dozen potentially interesting detections < 100 GeV, including ms pulsars in the GPS (30 h max exposure) -> Update needed
- Deeper dedicated observations : more sources, more physics
- Note :
 - The importance of LST's in the South site for the **HE component**!
 - The importance of SST's in the South site for the VHE component!
- The Vela pulsar detection in the multi-TeV range opens an exciting new perspectives for pulsar studies

CTA Observations

- Targets :
 - Their *prior definition* (as much as possible) is *mandatory* to be able to coordinate for getting the **ephemerides**
 - Their number depends on CTA ability to mobilise pulsar community (radio, X-rays)
 - Fermi-LAT is essential for γ-ray only PSRs
 - Can we hope for a few years overlap with Fermi?
 - Better modelling of Crab and Vela will certainly help
- **Observations** : Few strategies can be anticipated :
 - Survey : search for pulsars in the Galactic Plane using the GPS data
 - Single target : deeper observations for whatever reason, e.g.to :
 - Confirm hints in the GPS data
 - Study its light curve and spectrum (e.g. spectral cut-offs, evolution with energy, ...)
 - Monitor the pulsar e.g. during a MWL campaign on giant pulse counterpart search or in a period anticipating a glitch, etc
 - ToO : alerts of what ever origin (e.g. glitches)

MAPPED RADIO FACILITIES

- Low Frequency Radio
- mm /sub-mm Radio
- Mid-Hi Frequency Radio
 * * monitoring / follow-up?

Recent/New/Future ground-based Instruments (to be updated)

Radio

- SKA Australia-SA: certainly the main player for pulsar science (Southern sources)
 - 3 phases (with pathfinders ASKAP, MeerKAT, MWA, ...)
 - SKA1 (Lo-Mid) : 2020+
 - SKA2 (Lo-Mid) : 2023+
 - SKA3 (Hi) : 2025+
- FAST China : New in the landscape in China : 2017 +
 - Routine timing or specific targets?
- QT (Qitai)- China : 2023 + :
 - 110 m; planned 300MHz-117 GHz; pulsars are one of main drivers
- USA :
 - New telescopes being discussed for the IPTA (Int. Pulsar Timing Array)
 - Large efforts for proposing NGVLA (but specific use for GC pulsars to study GR).
- EU : large efforts for EPTA (European Pulsar Timing Array)
 - Faith of current instruments/upgrades could/will rely on EPTA funding
 - Effelsberg (Ge),Lovell (UK), Nançay (Fr), SRT (It), WSR (NL)

Other WLs, space-based

• still need to complete the list, but other than Fermi-LAT (if in operation) none is foreseen to serve for routine monitoring, rather specific cases

Summary & Perspectives

- Four pulsars are now detected from ground
- The young Crab, the elder Vela & PSRB 1706-44 + the "old" Geminga pulsar
- Differences!
 - Crab : GeV component extends with a power-law tail, extending to ~1 TeV
 - Vela : GeV component most probably cuts off < ~100 GeV, but second component takes over in the multi-TeV range
 - Question is still open for B1706-44 and Geminga
 - Others?!
- VHE component brings in precious probes into the pulsar systems, e.g. maximum energy of acceleration and emission processes
- Crucial question: distinction between magnetospheric and wind-based models
- Current generation IACT results and observations are essential for setting the stage for pulsar physics with CTA:
 - The >10 better sensitivity of CTA will be of great importance to pulsar physics two important energy ranges :
 - TeV to tens of TeV, i.e. the "VHE component" per se : Vela-like psrs?
 - 20 to < 300 GeV : "HE Component", Crab-like tail or cut-off?
- Observation strategy and prior coordination with other instruments is mandatory

Geminga : VERITAS 2015

[Aliu et al. 2015]

- Exposure = 72 hours
- No signal > 100 GeV

Search for > 50 GeV with Fermi-LAT

[McCann et al. 2015]

- Stacking of 115 pulsars
- Exposure = 4.2 years on average for each
- No signal > 50 GeV
- Subsets tested :
 - Young
 - MSPs
 - Still no signal

Survey of 13 pulsars with VERITAS

[Richards, et al. 2017+2018]

- Archival data on 14 "young" and nearby pulsars
- Exposure = from 3 to 108 h
- Total exposure = 483.8 h
- 3 sets of cuts corresponding to energy threshold from 126 GeV to 1 TeV
- No signal found

Pulsar	R.A. (°)	Dec. (°)	$P(\mathbf{s})$	$\dot{P}(10^{-15})$	\dot{E} (10 ³⁴ erg s ⁻¹)) Distance (kpc)	\dot{E}/d^2 Rank	VERITAS
								Exposure (hr)
J0007+7303	1.7565	73.0522	315.9	357.	44.8	1.4 ± 0.3 [170]	9	32.4
J0205+6449	31.4080	64.8286	65.7	190.	2644.	1.95 ± 0.04 [171]	3	22.2
J0248+6021	42.0776	60.3597	217.1	55.0	21.2	2.0 ± 0.2 [172]	11	45.9
J0357+3205	59.4680	32.0891	444.1	13.1	0.6	$0.5^{+0.4}_{-0.2}$ [173]	14	7.92
J0631+1036	97.8657	10.6165	287.8	104.	17.3	1.0 ± 0.2 [174]	10	2.79
J0633+0632	98.4339	6.5418	297.4	79.6	11.9	< 8.7	-	108
J1907+0602	286.9782	6.0374	106.6	86.7	282.	3.2 ± 0.3 [175]	8	39.1
J1954+2836	298.5798	28.6013	92.7	21.2	105.	< 18.6	-	5.18
J1958+2846	299.6667	28.7653	290.4	212.	34.2	< 18.5	-	13.9
J2021+3651	305.2726	36.8513	103.7	95.6	338.	$1.8^{+1.7}_{-1.4}$ [176]	4	58.2
J2021+4026	305.3781	40.4461	265.3	54.2	11.4	1.5 ± 0.4 [177]	12	20.6
J2032+4127	308.0548	41.4568	143.2	20.4	27.3	3.7 ± 0.6 [178]	15	47.9
J2229+6114	337.2720	61.2359	51.6	77.9	2231.	$0.80^{+0.15}_{-0.20}$ [179]	2	47.2
J2238+5903	339.6173	59.0624	162.7	97.0	88.8	< 12.4	-	32.5

Survey of 13 pulsars with VERITAS

[Richards, et al. 2017+2018]

Soft Cuts

- Upper limits :
- Compared to $\sqrt{(\dot{E})}/d^2$
- Soft and Hard cuts
- Vela extrapolation is based on a power-law but which is disfavoured by HESS-II
- All limits in the range : ~10⁻¹² - 10⁻¹³ erg/cm2/s

