Optical, ultraviolet, infrared follow-ups of *Fermi* pulsars

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Abstract: The wealth of pulsar detections by *Fermi* paved the way to multi-wavelength follow-ups to extend the characterisation of their spectral and timing properties. Being pulsars quite faint in the optical, ultraviolet, and infrared, this has required observations with 8m-class telescopes and with the *HST*. In this poster we briefly summarise 10 years of follow-ups of *Fermi* pulsars in these spectral regions.

The copious detection of γ-ray pulsars by the Fermi Large Area Telescope (LAT), with 216 of them identified since the launch of the satellite in 2008, makes them the largest class of identiifed Galactic γ-ray sources. The harvest of pulsar γ-ray detections has fostered the interest on their multi-wavelength studies, especially in the X-rays and in the optical (O), ultraviolet (UV), infrared (IR) -**UVOIR** for short- to characterise their spectral energy distribution (SED) and study the interplay between different emission mechanisms. Pulsars are intrinsically very faint in the UVOIR domain, where they are detected only through the emission of synchrotron radiation from relativistic particles in their magnetosphere (power law spectra with α =0-1) and/or thermal radiation from their hot (brightness temperatures 0.1-1 MK) surface. Thus, they are challenging targets in the UVOIR and very few of them have been identified.

TABLE 1: γ-ray pulsars Identified *before* the launch of *Fermi*

NAME	P(ms)	Log(Age)	Log(Edot)	Mag	Band	D(kpc)	Ref
Crab	33 [$P_{OPT,UV,IR}$]	3.10	38.65	V=16.6 [36 inch]	UVOIR	2	Cocke et al., 1969, Nature, 221, 525
PSR B1509-58	151	3.19	37.25	R=25.7 [VLT]	OIR	4.2	Wagner & Seifert, 2000, ASP, 202, 315
PSR B0540-69	50 [$P_{OPT,UV}$]	3.23	38.69	V=22.5 [NTT]	UVOIR	48.9	Caraveo et al., 1992, ApJ, 395, 103
Vela	89 [$P_{OPT,UV}$]	4.05	36.84	V=23.6 [Blanco]	UVOIR	0.287	Lasker, 1976, ApJ, 203, 193
PSR B0656+14	384 [$P_{OPT,UV}$]	5.05	34.58	V=25 [NTT]	UVOIR	0.288	Caraveo et al., 1994, ApJ, 422, L87
Geminga	237 [$P_{OPT,UV}$]	5.53	34.51	V=25.5 [NTT]	UVOIR	0.250	Bignami et al., 1993, Nature, 361, 704
PSR B1055-52	197	5.73	34.48	V=25.5 [HST]	UVO	0.350	Mignani et al., 1997, ApJ, 474, L51
PSR J0437-5715	5.96	9.69	33.58	V~25^{extr} [HST]	UV	0.139	Kargaltsev et al., 2004, ApJ, 602, 372

Till recently, the γ-ray pulsars identified in in at least one of the UVOIR energy bands were mostly those originally detected by *SAS-2* and *COS-B* in the 1970s/1980s (the **Crab** and **Vela** pulsars, **Geminga**) or by the *Compton Gamma-ray Observatory* (**PSR B0656+14, PSR B1055-52, PSR B1509-58**). PSR B1706-44 and PSR B1951+32 are the only two *Compton* γ-ray pulsars that are still unidentified in the UVOIR. Table summarises all γ-ray pulsars identified in at least one UVOIR band before the launch of *Fermi*, mostly in the 1990s. The Large Magellanic Cloud **PSR B0540-69** and the old, recycled milli-second pulsar (MSP) **PSR J0437-4715** [both marked in red] were identified well ahead of their detection as γ-ray pulsars by *Fermi*. PSR J0437-4715 is also the only binary MSP identified in the UVOIR. There are only five γ-ray pulsars (Crab, Vela, PSR B0540-69, Geminga, PSR B0656+14) detected in all the UVOIR bands (Mignani et al. 2018a, submitted to ApJ, arXiv:1809.10805). The pulsars marked as [$P_{OPT,\,UV}$] are those pulsating in the optical and in the UV. Only the Crab, [$P_{OPT,UV,IR}$], also pulsates in the IR.

TABLE 2: γ-ray pulsars Identified *after* the launch of *Fermi*

NAME	P(ms)	Log(Age)	Log(Edot)	Mag	Band	D(kpc)	Ref
PSR J0205+6449	65	3.73	37.43	r'=26.2 [Gem]	O	3.2	Moran et al., 2013, MNRAS, 436, 401
PSR J1357-6429	166	3.86	36.49	J=23.5 [VLT]	IR	2.4	Zyuzin et al., 2016, MNRAS, 455, 1746
PSR J1741-2054	413	5.58	33.97	V=25.3 [VLT]	O	0.38	Mignani et al., 2016, ApJ, 825, 151
PSR J2124-3358	4.93	9.58	33.83	B=27.5 [HST]	UVO	0.41	Rangelov et al., 2017, ApJ, 835, 264

UVOIR candidate counterparts to γ-ray pulsars have been identified after the launch of *Fermi* exploiting the collecting power of 8m-class ground-based telescopes deployed in the late 1990s and the UV sensitivity of the *HST*. **PSR J0205+6449** was identified using archival data from the Gemini North telescope but the other three pulsars were identified thanks to dedicated follow-ups with the VLT (**PSR J1357-6429**, **PSR J1741-2054**) and the *HST* (**PSR J2124-3358**). Table 2 summarises the new candidate identifications, with PSR J2124-3358 being the first isolated MSP identified in the UVOIR. For none of them UVOIR pulsations have been detected yet, both owing to the relatively recent counterpart identification and to the paucity of instruments for high-time resolution observations. This γ-ray pulsar identification rate [0.4 yr^{-1}] compares favourably with that before the launch of *Fermi* [~0.2 yr^{-1}] but not much so when considering the factor of ~30 increase in the number of γ-ray pulsars, even accounting for the few years needed for the identification process. The identification effort continued restlessy, though.

TABLE 3: γ-ray pulsars Observed *after* the launch of *Fermi*

NAME	P(ms)	Log(Age)	Log(Edot)	Mag	D(kpc)	Ref
PSR J0007+7303	316	4.14	35.65	r'>27.6 [GTC]	1.4	Mignani et al., 2013, MNRAS, 430, 1354
PSR J2021+3651	104	4.23	36.53	r'>27.2 [GTC]	1	Kirichenko et al., 2015, ApJ, 802, 17
PSR J1907+0602	106	4.29	36.44	V>26.9 [VLT]	2.58	Mignani et al., 2016b, MNRAS, 463, 2932
PSR J1048-5832	123	4.30	36.30	V>27.6 [VLT]	2.7	Razzano et al., 2013, MNRAS, 426, 3636
PSR J0631+1036	287	4.64	35.23	g'>27 [GTC]	1.0	Mignani et al., 2016a, MNRAS, 451, 4317
PSR J0633+0632	297	4.77	35.08	g'>27.3 [GTC]	<8.7	Mignani et al., 2016a, MNRAS, 451, 4317
PSR J0248+6021	217	4.79	35.32	g'>27.3 [GTC]	2.0	Mignani et al., 2016a, MNRAS, 451, 4317
PSR J1809-2332	146	4.83	35.63	V>27.6 [VLT]	1.7	Mignani et al., 2016b, MNRAS, 463, 2932
PSR J1028-5819	91	4.95	35.92	V>25.3 [VLT]	2.3	Mignani et al., 2012, A&A, 543, 130
PSR J1846+0919	225	5.55	34.53	g'>27.0 [GTC]	1.4	Mignani et al., 2018b, MNRAS, 478, 332
PSR J0357+3205	444	5.74	33.76	g'>28.1 [GTC]	0.5	Kirichenko et al., 2014, A&A, 564, 81
PSR J2043+2740	96	6.08	34.74	g'>27.2 [GTC]	1.48	Mignani et al., 2018b, MNRAS, 478, 332
PSR J2055+2539	319	6.09	33.69	g'>26.8 [GTC]	0.6	Mignani et al., 2018b, MNRAS, 478, 332

Follow-up observations of *Fermi* γ–ray pulsars continued on the [supposedly] best candidates but were hampered in some cases by the uncertain distance estimate, without known radio parallaxes, by the lack of accurate radio or *Chandra* coordinates, and by the uncertain extinction determination, which relies on X-ray observations to infer the N_H from the spectral fits. Thus, the chances of success of UVOIR follow-ups depend on coordinated radio/X-ray observations, which also imposes a physiological delay in the identification process. In most cases it was possible to set deep constraints on the UVOIR flux, though. Table 3 summarises follow-ups of γ-ray pulsars with 8m-class telescopes (optical band only). In all cases the detection limits are between magnitude ~27 and 28, i.e. close to the limits of current facilities. A compilation of detection limits for γ-ray pulsars observed prior to their detection by *Fermi* can be found in the Second γ-ray Pulsar Catalogue (Abdo et al. 2013, ApJS, 208, 17). As it can be seen (Table 2, 3), most of the observational effort has relied on European telescopes (GTC,VLT), with *HST* focussed on follow-ups of identified pulsars (e.g., Mignani et al. 2018a) and Subaru, Keck, Gemini, LBT essentially unused – resources to be exploited in the future.

Summary: The UVOIR follow-ups of γ-ray pulsars show that the SEDs commonly feature breaks between the high and low-energy power-law spectra and do not follow a unique template even in pulsar with similar characteristics (e.g., Mignani et al. 2016), suggesting that the topology of the emission regions, the beaming and viewing geometry play an important role. UVOIR timing observations, in parallel to X and γ-ray ones, are crucial to address this issue. In relative terms, the UVOIR luminosity is a small fraction of the X and γ-ray ones, where the ratio span from -3.2 to -4.7 [in logarithmic units] in the X-rays and from -2.6 to -7.2 in γ-rays showing that in the latter case the relative yield is more variable, perhaps owing to a different emission configuration between the X and γ-rays. The UVOIR pulse profiles are, generally, not aligned with the γ-ray ones, with the exception of the Crab pulsar and PSR B0540-69, where they feature a remarkable alignment and similarity. Among the identified γ-ray pulsars, **PSR B1055-52** and **PSR J1741-2054** are, probably, the next best targets to search for optical/UV pulsations.