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PULSARS ALL ACROSS THE SPECTRUM

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Abstract. Pulsars, rotating magnetized neutron stars born in supernovae, are fascinating objects and their study finds applications in a wide range of physics and astrophysics. *Fermi* Large Area Telescope observations have shown that they form the main class of GeV gamma-ray sources in the Milky Way, and the detection of the Crab pulsar beyond 100 GeV by Cherenkov telescopes has opened a new window on their study at even more extreme energies. At the other end of the spectrum, radio observations over the last five years have doubled the number of known millisecond pulsars, those that rotate hundreds of times every second and that constitute unique gravity laboratories. Radio timing observations of an array of stable millisecond pulsars can also be used to search for low frequency gravitational waves from distant massive black hole binaries. I review recent results on pulsars and discuss future prospects for the study of these extreme objects, all across the spectrum.

Keywords: pulsars, pulsar timing, gamma rays, general relativity, gravitational waves

1 Introduction

Since the original discovery of a pulsar nearly fifty years ago (Hewish et al. 1968), more than 2300 of these fascinating objects have been observed, from radio observations in a vast majority of cases. Pulsars are rapidly-rotating neutron stars, thought to have radii of about 10 km and with measured masses of up to two solar masses (Antoniadis et al. 2013), making them the densest objects observable. They have large magnetic fields of $10^8 - 10^{15}$ G, and their magnetosphere is filled with plasma. Pulsars produce electromagnetic emission in the form of beams that are swept across the sky as they rotate, so that distant observers – provided that the emission is beamed toward them – see pulsars as periodic sources of emission. In fact, the periodicity of the observed emission, and the rate at which the period increases, give us a great deal of information about the pulsar responsible for the emission. Figure 1 shows the measured rotation periods P and their time derivatives $\dot{P} = dP/dt$ for currently known pulsars. Two main pulsar populations can easily be distinguished from this diagram: a category of about 2000 "normal" pulsars with $P \sim 0.1 - 1$ s in the upper right corner, and so-called "millisecond pulsars" (MSPs) in the lower left part of the plot, with rotation periods in the order of 1 ms and comparatively smaller values of $\dot{P}$. MSPs are thought to have acquired their low rotation periods by accretion of matter and thus transfer of angular momentum from a binary companion (Bisnovatyi-Kogan & Komberg 1974; Alpar et al. 1982). The values of P and $\dot{P}$ also inform us about the basic properties of pulsars: for instance, denoting I as the neutron star moment of inertia and $\Omega = 2\pi/P$ the angular velocity, the rotational kinetic energy $E_{\rm rot}$ is given by $\frac{1}{2}I\Omega^2$. Because pulsars slow down gradually, this energy budget varies at a rate $dE_{\rm rot}/dt = I\Omega\dot{\Omega} = -4\pi^2 I \frac{\dot{P}}{P^3}$. This quantity, noted $\dot{E}$, is called the "spin-down power" and traces the amount of energy loss that can go into electromagnetic radiation. In Section 2 we will see that pulsars with the highest $\dot{E}$ values are often detected as sources of high-energy radiation.

Pulsar observations find their applications in numerous fields of Physics and Astrophysics, from e.g. plasma physics and electrodynamics to tests of theories of Gravity, gravitational wave searches or studies of the neutron star equation of state, to name but a few examples. As in other fields of astronomy, one can study pulsars by recording and describing their temporal and spectral emission properties, at a given energy or across the electromagnetic spectrum to get complementary information. Figure 2 shows radio, X-ray and gamma-ray

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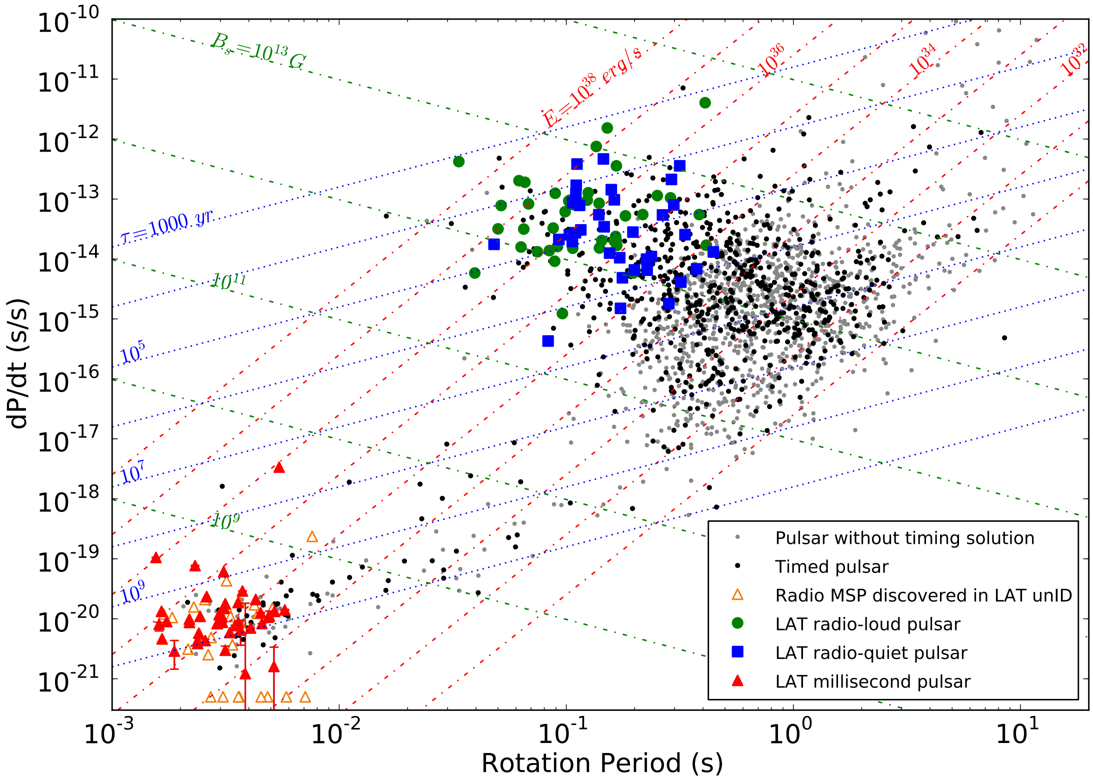

Fig. 1. Spin-down rate $\dot{P} = dP/dt$ versus rotation period P for known pulsars. Colored symbols (red triangles, blue squares and green circles) indicate pulsars detected by the *Fermi* LAT as pulsed sources of GeV gamma-ray emission. Also shown on this plot are lines of constant spin-down power $\dot{E}$, they are represented by the dashed red lines. Figure taken from Abdo et al. (2013), see this article for a complete description.

pulse profiles for the MSP B1821−24A in the globular cluster M28. Peak locations, multiplicities, shapes, and relative positions across the spectrum inform us about the physical mechanisms at play, and the geometry of the emission beams. Likewise, spectral measurements at different wavelengths give important clues about particle acceleration sites, physical processes involved, and emission energetics.

Another channel commonly used for studying pulsars is to do “pulsar timing”. In pulsar timing, each rotation of a pulsar over a given time span (months to years or even more) is unambiguously accounted for, and the precise tracking of the pulsar’s rotational phase enables sensitive measurements of phenomena affecting its rotation, binary motion, or perturbing the propagation of its signals through space. A detailed description of the technique and of its applications can be found in e.g. Lorimer & Kramer (2005). In practice, the technique gives its best results for MSPs, which are incredibly stable clocks. An illustration of the great stability of MSPs is shown in Figure 3: in this case, the root-mean-square (RMS) deviation of the differences between observed and predicted ticks from PSR J1909−3744 is smaller than 100 ns over five years! As a consequence, pulsar timing enables measurements of some physical quantities with fantastic precision. Examples of the applications of pulsar timing are given in Section 3.

The aim of these proceedings is not to give a full review of recent results of pulsar observations in different wavelength domains, but rather highlight some salient results and show some examples of the complementarity of multi-wavelength (or multi-energy) observations of pulsars.

2 Pulsars as sources of high-energy emission

The launch of the *Fermi* satellite in June 2008 marked the start of a new era in high-energy pulsar observations. Before the Large Area Telescope (LAT), main instrument on *Fermi*, started observing, fewer than ten pulsars

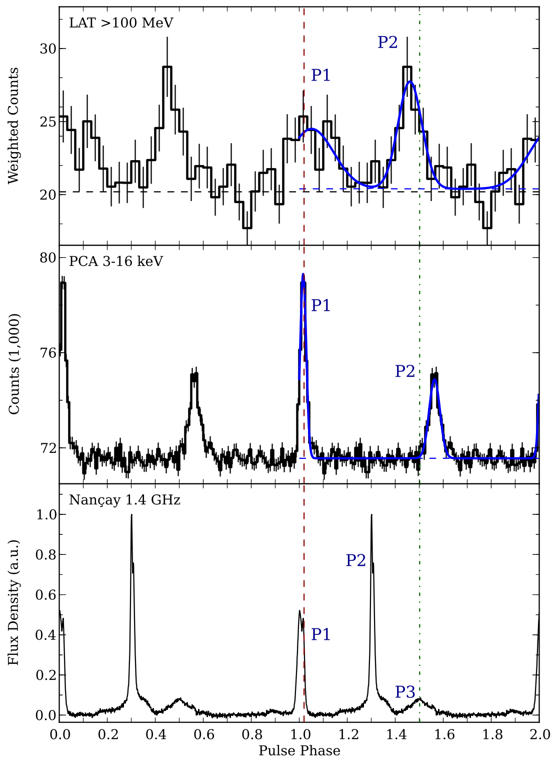

Fig. 2. Pulse profiles of PSR B1821−24A in the globular cluster M28, at different wavelengths. Bottom panel: 1.4 GHz Nançay profile. Middle panel: RXTE X-ray observation between 3 and 16 keV. Top panel: *Fermi* LAT gamma-ray observation above 0.1 GeV. Two full pulsar rotations are shown. See Johnson et al. (2013) for additional details on these profiles.

were known to emit GeV gamma rays. Attempts to understand the fundamental processes responsible for the high-energy emission from pulsars were thus confronted to a severe lack of observational data and of variety in the sample of known gamma-ray pulsars. The situation six years after the LAT began its observations of the GeV gamma-ray sky has changed dramatically, and the LAT has revolutionized our view of the gamma-ray pulsar population. As of September 2014, a total of 147 pulsars have been detected as pulsed sources of GeV gamma-ray emission, including more than 60 MSPs (all of them also detected as radio emitters), and the rest of normal pulsars, radio-loud or radio-quiet*. Figure 4 shows the locations of *Fermi* LAT detected pulsars on a map in Galactic coordinates, along with the locations of other known pulsars from the ATNF pulsar catalog† (Manchester et al. 2005). The pulsars were detected by either blind searching LAT sources for pulsations (e.g., Pletsch et al. 2013), or by folding the LAT photons at their apparent rotation periods as measured from supporting pulsar timing observations in the radio (see e.g., Guillemot et al. 2013; Ng et al. 2014). As the mission progresses, new gamma-ray pulsars continue to be detected (Hou et al. 2014), including less luminous pulsars or ones with broad gamma-ray pulses, making them difficult to distinguish from the background emission.

The second *Fermi* LAT catalog of gamma-ray pulsars (hereafter 2PC; Abdo et al. 2013) includes 117 gamma-ray pulsars detected using three years of LAT data, and represents the latest systematic effort to analyze and describe the properties of the population of GeV gamma-ray pulsars. A majority of 2PC pulsars have two gamma-ray peaks in their profiles, and with a few notable exceptions (e.g., Guillemot et al. 2012) the gamma-ray emission is separated from the radio emission, when present. Light curve modeling (e.g., Johnson et al. 2014) indicates that gamma-ray emission originates from the outer magnetosphere, in the form of fan-like beams

*See `https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars` for an up-to-date list of *Fermi* LAT detected pulsars.

†`http://www.atnf.csiro.au/people/pulsar/psrcat/`

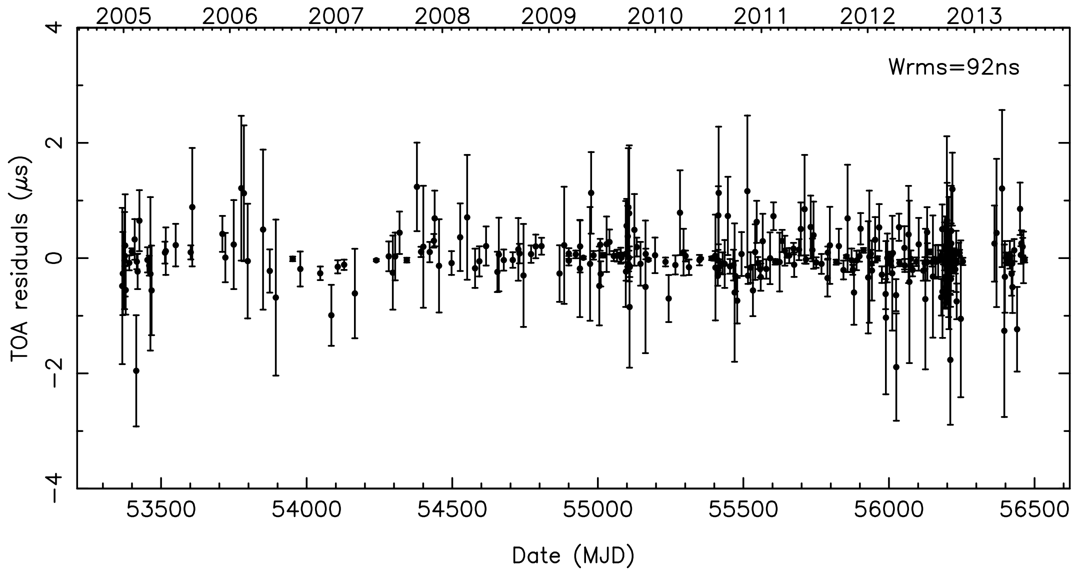

Fig. 3. Plot showing the difference between the observed times of arrival of radio pulses from the MSP J1909−3744 at the Nançay Radio Telescope and those predicted by a model (so-called "residuals"), as a function of time. The RMS of the residuals for the data shown in this plot is 92 ns.

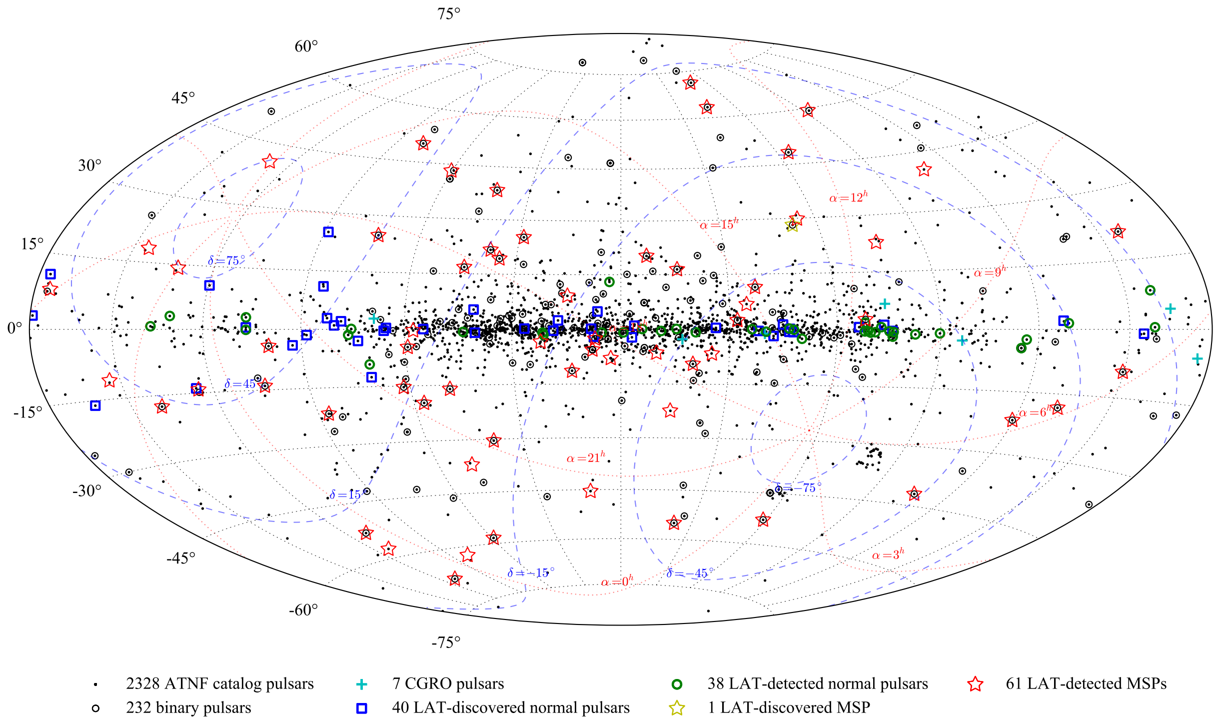

Fig. 4. Sky map in Galactic coordinates showing the locations of pulsars listed in the ATNF pulsar catalog, with pulsars detected as pulsed sources of gamma rays by the *Fermi* LAT represented as colored symbols. Lines of constant Right Ascension (respectively, Declination) are represented with red dotted lines (resp., blue dashed lines).

sweeping large portions of the sky. Spectral measurements also favor outer magnetospheric emission as opposed to gamma-ray emission from near the stellar surface: the spectra of most gamma-ray pulsars is indeed consistent with curvature radiation with no suppression caused by magnetic attenuation, as expected for emission produced away from the surface. Gamma-ray emission is only observed for high $\dot{E}$ pulsars (see Figure 1). Undetected pulsars with high $\dot{E}$ values could be too distant, leading to small gamma-ray fluxes, they can be embedded in regions of intense gamma-ray background emission, have broad gamma-ray emission profiles making them difficult to detect with commonly-used statistical tests (see Hou et al. 2014), or may simply not beam their gamma-ray emission in the direction of the Earth. On the other hand, LAT-detected pulsars have large gamma-ray efficiencies (ratio of the gamma-ray luminosity to the spin-down power $\dot{E}$) ranging from $\sim 1\%$ to 100%. Investigations of the photons with large energies also revealed that the LAT detects significant pulsations from 20 pulsars above 10 GeV, and from 12 pulsars above 25 GeV (Ackermann et al. 2013), confirming the very high energy detection of pulsations from the Crab pulsar by the MAGIC and VERITAS telescopes (Aliu et al. 2008; VERITAS Collaboration et al. 2011). Such high and very high energy detections of pulsars are important for understanding the fundamental processes at play in pulsar magnetospheres.

Another great success of the *Fermi* mission in terms of pulsar science is the discovery of many new gamma-ray sources with high energy emission properties similar to those of known gamma-ray pulsars, and that can be searched for pulsations either directly in the LAT data, or at other wavelengths. For example, optical and X-ray observations of the bright source with pulsar-like properties J1311.7−3429 from the 2FGL catalog of LAT sources (Romani 2012; Nolan et al. 2012) revealed a binary system with a 1.56-hr orbital period, and the partial constraints on the orbital parameters from this study allowed Pletsch et al. (2012) to discover the gamma-ray pulsations from the 2.5 ms pulsar J1311−3430 by blind searching the LAT data. J1311−3430 is the only example thus far of an MSP discovered by blind searching the LAT data. However, it is not yet the first example of a radio-quiet MSP, as Ray et al. (2013) detected weak radio pulsations from this object soon after its discovery. On the other hand, observations of *Fermi* LAT's previously unknown sources with pulsar-like emission properties in the radio domain have enabled the discovery of many new radio and gamma-ray MSPs (e.g., Ransom et al. 2011; Cognard et al. 2011; Barr et al. 2013): more than 60 as of today[‡], about 30% of the currently known population of Galactic disk MSPs. *Fermi* has therefore provided a vital contribution to the hunt for Galactic disk MSPs, and more MSPs will be found as new gamma-ray sources are discovered.

3 Science from timing observations of pulsars

As highlighted in the introduction, another common way of studying pulsars and their environment is through the so-called "pulsar timing" technique. In pulsar timing, times of arrival of pulses are recorded at a telescope and are used to count every single rotation of the pulsar. In this experiment, pulsars are therefore used as clocks, and perturbations in the "ticks" of these clocks allow us to measure and study many types of physical phenomena, especially if the pulsar belongs to a binary system (about 10% of known pulsars do).

A first famous example of a binary pulsar laboratory is the system formed by the 59-ms pulsar B1913+16 and its companion, also thought to be a neutron star but undetected as of now (Hulse & Taylor 1975). By timing B1913+16 in the radio, the discoverers rapidly came to the conclusion that the orbits of the stars in this system are not well represented by simple Keplerian orbits. In particular, the measurement of the decay of PSR B1913+16's orbit at a rate compatible with the predictions of Einstein's general relativity (GR) provided the very first evidence for the existence of gravitational waves. About ten years ago, the discovery of the double pulsar J0737−3039 (Burgay et al. 2003; Lyne et al. 2004), the unique case so far of a double neutron star system in which both objects are detected as radio pulsars, has provided pulsar astronomers with an even better laboratory for testing GR. The timing of the pulsars in this system allowed Kramer et al. (2006) to measure five post-Keplerian (PK) parameters (i.e., corrections to the Keplerian description of orbital motion), all of them for the fastest rotator in the binary, the 22-ms pulsar J0737−3039A: the advance of periastron in its orbit, the gravitational redshift parameter, the orbital period derivative, and two parameters describing the "Shapiro delay" induced by the deformation of space-time around its companion. By measuring the geodetic precession of the 2.8-s pulsar J0737−3039B, Breton et al. (2008) were able to determine a sixth PK parameter. Comparisons of the measured PK parameters in the double pulsar system with the expectations from GR have enabled the most precise tests of GR in the strong field regime done yet. In particular, the Shapiro delay parameter s measured by Kramer et al. (2006) agrees with the value predicted by GR at the 0.05% level. Recently, pulsar searches conducted with the Green Bank Telescope uncovered the 2.73-ms pulsar J0337+1715, a millisecond pulsar in a triple system with two other stars (Ransom et al. 2014). In this system, the radio MSP is in a short, 1.63-d orbit around a 0.20 $M_{\odot}$ white dwarf, and this inner binary system is itself in a wide,

[‡]See `http://astro.phys.wvu.edu/GalacticMSPs/GalacticMSPs.txt`

327.3-d orbit around a 0.41 $M_\odot$ companion, also white dwarf. PSR J0337+1715 is not the first case of a pulsar found to be in a triple system: PSR B1620−26 has a white dwarf companion and a Jupiter-mass companion (Thorsett et al. 1999), but in contrast with the latter system, the timing of PSR J0337+1715 reveals strong gravitational interactions between the three bodies in the system that need to be accounted for to properly model the pulsar's spin behavior. One promising application of the continued timing of PSR J0337+1715, when the effects affecting its motion are understood and well modeled, will be to test the strong equivalence principle (SEP) of GR: i.e., are the pulsar and the inner white dwarf falling in the gravitational field of the outer white in the same manner, in spite of their very different gravitational binding energies? If so, then alternative theories of gravity predicting such SEP violations will be ruled out by this experiment.

Another famous application of pulsar timing is the possibility to search for gravitational waves *directly*, with Pulsar Timing Arrays (e.g., Foster & Backer 1990). In a PTA experiment, the timing residuals of an array of very stable pulsars are analyzed jointly, to search for correlated perturbations tracing the passage of gravitational waves (GWs). Indeed, while pulsar rotation irregularities will induce timing residuals that are different between the pulsars, or other effects will affect the residuals of different pulsars identically (e.g., errors in the time standard), the phase and amplitude of residuals caused by gravitational waves is expected to depend on the pulsar directions with respect to the source. PTAs are sensitive to GWs with ultra-low frequencies of order $10^{-9} - 10^{-7}$ Hz. They are thus complementary to ground- and space-based GW detectors operating at much higher GW frequencies, such as LIGO and eLISA. Several collaborations have formed around the world, to search for GWs using the pulsar data recorded at different large radio telescopes. The Parkes Pulsar Timing Array (PPTA, Manchester et al. 2013) uses data from the Parkes radio telescope. The North American Nanohertz Observatory for Gravitational Waves (NanoGRAV, McLaughlin 2013) searches for GWs using pulsar timing data taken at the Green Bank and Arecibo radio telescopes. The European Pulsar Timing Array (EPTA, Kramer & Champion 2013) uses data from Jodrell Bank, Westerbork, Effelsberg, Nançay and Sardinia radio telescopes. Finally, the three collaborations form the International Pulsar Timing (IPTA, Manchester & IPTA 2013). Sources of GW emission that PTAs could be sensitive to are for instance supermassive black hole binaries or cosmological sources (cosmic strings, inflation era, etc.). A recent upper limit on a stochastic gravitational wave background is the one published by the PPTA collaboration (Shannon et al. 2013): by timing six highly stable pulsars for about 11 years, and assuming a slope of $-2/3$ for the red power spectrum induced by the GW background on the timing residuals, they placed a 95% upper limit on the characteristic strain h_c of 2.4×10^{-15}. Such a limit places useful constraints on the population of supermassive black hole binaries. The sensitivity of PTAs will continue to increase as more highly stable pulsars are discovered and added to PTAs, as the data sets get longer, as the timing precision on individual time of arrival measurements is improved (through e.g. instrumentation upgrades) and as sources of noise contaminating the timing data are understood and modeled better. By discovering many more highly stable MSPs and measuring times of arrival of radio pulses with much higher precision, future radio instruments such as the SKA[§] will increase the sensitivity of GW searches using PTAs dramatically.

4 Conclusions

In these proceedings I have reviewed some recent results from pulsar observations at different wavelengths. The list of examples chosen in the present document is far from exhaustive, yet it illustrates the importance of multi-wavelength observations of pulsars and the synergies that exist across the electromagnetic spectrum. The prospects for future pulsar observations are promising. With its enormous collecting area and frequency coverage, the SKA is expected to discovery many thousands to new radio pulsars (Smits et al. 2009), including hundreds in highly relativistic binaries allowing even more stringent tests of GR, and highly stable pulsars that can serve to search for GWs with PTAs. The SKA might also detect radio pulsars in compact orbits around the supermassive black hole at the center of the Milky Way, and the subsequent timing of these pulsars would then enable precise tests of the cosmic censorship conjecture and of the no-hair theorem (Liu et al. 2012). In a nearer future, observations with LOFAR[¶] or with NenuFAR[‖] will explore the very low radio frequency emission from pulsars and will be able to characterize the electron contents of the interstellar medium that induce strong dispersive delays at these low radio frequencies with unprecedented sensitivity. At the other end of the spectrum,

[§] Square Kilometre Array, see `https://www.skatelescope.org/`

[¶] Low-Frequency Array, `http://www.lofar.org/`

[‖] New Extension in Nançay Upgrading LOFAR, see `http://nenufar.obs-nancay.fr/?lang=en` the *Fermi* LAT will detect more gamma-ray pulsars and find more sources in which to search for new radio pulsars, until the end of its activity. During the first half of the mission, the LAT has already demonstrated that pulsars constitute the dominant class of GeV gamma-ray sources in the Galaxy. The detection of pulsed emission above 10 and even 25 GeV for a number of pulsars, and the detection of Crab pulsations by Cherenkov telescopes at even more extreme energies have opened a new window on the study of pulsars and pulsar emission mechanisms in very high energy gamma rays. In this context, the advent of CTA**, the future ground-based very high energy gamma-ray observatory, is much anticipated.

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