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Advancing pulsar science with the FAST

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As the rump left behind after an extremely gravity-induced supernova of an evolved massive star, a pulsar is made of cool CBM (i.e., compressed baryonic matter at a low temperature). Pulsars are not only testbeds for fundamental interactions (e.g., the nature of gravity [1] and of the strong force at low energies [2]), but also essential tools for detecting nano-Hz gravitational waves [3]. The pulsar science, whatever, usually depends on the measurement of pulsar radiation, e.g., pulsar *monitoring* and *timing*. Additionally, *searching* new pulsars for further investigation is also an important focus of this research field.

Pulsars have a very good showing, and have never stopped presenting surprises since the first discovery in 1967, because of the continuing development of advanced facilities. The biggest single-dish radio telescope in the world, i.e., the Chinese Five-hundred-meter Aperture Spherical radio Telescope (FAST), is going to regularly observe pulsars , with extremely high sensitivity but without requiring the complicated data processing required for an antenna array. The signal-to-noise ratio is $\propto A\sqrt{t}$, where A denotes the effective area and t denotes the observing time. Thus a one-minute observation with the FAST is comparable to a 10-hour observation with a 60-meter telescope if the same receiver can remain stable for such a long time. Therefore, we anticipate a FAST era of pulsar science to come.

In this essay, we discuss the potential for obtaining remarkable achievements in pulsar science with the FAST, including pulsar monitoring, timing and searching, as well as other related areas of research.

(1) Pulsar monitoring

The FAST with high-sensitivity can provide high signal-to-noise ratio data, with subtle and dynamical structural information. This indicates that it is not always necessary to superimpose pulses during the analysis and the change between the pulse sequence of different cycles can be accurately determined. New data dimensions (e.g., phase and polarization) beyond frequency will be opened up for more information. Further, the correlation between multiple sets of data dimensions could open a new window for understanding the pulsar magnetospheric activity [4].

Single pulse phenomena, e.g., drifting sub-pulse, pulse nulling, mode change and giant pulse, were observed in some pulsars. High signal-to-noise ratio data will allow these phenomena to be found in more pulsars, and new manifestations of these phenomena can be analyzed [5, 6]. The single-pulse phenomenon is related to physical processes in the pulsar magnetosphere, and studying the behavior and statistical properties of single pulses can help to analyze the radiation mechanism [7].

Pulsar is a powerful tool for studying the interstellar medium. The FAST will provide high precision data for measuring the distribution and turbulence of the interstellar medium (not only for free electrons, but also for atomic

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gases [8]). Furthermore, the polarization-calibrated data can be used to determine the interstellar magnetic fields [9].

The physical environment of a pulsar, including strong electromagnetic fields, strong gravitational fields, and supranuclear dense matter, is extreme; it is difficult or intractable to study the aforementioned factors in terrestrial laboratories. Therefore, understanding the physical processes in pulsars may help to discover some fundamental details. Because of non-linearity, the physical processes in strong electromagnetic fields are very complex and difficult to calculate with certainty. Further, the non-perturbative quantum chromodynamics associated with the cool dense matter cannot even be theoretically solved. In contrast, the pulsar observation data can provide relevant information about these extreme situations.

(2) Pulsar timing

Pulsar orbital parameters (for pulsar binary/triple system) can be obtained via timing. From high precision orbital parameters, pulsar mass can be calculated in some cases. The pulsar mass is important for understanding the matter state and formation of pulsar. Conventional neutron star models do not allow pulsar masses to be greater than ~ 2.5 or less than 0.1 times the mass of the sun, but the strangeon star model does [2]. The mass distribution of isolated or binary pulsars limits the pulsar formation and evolution models.

General relativity (GR) is considered to be the standard theory for gravity. It is based on the assumption of the strong equivalence principle. However, there is no *ab-initio* argument to support this hypothesis. The orbits of the compact double pulsar system considerably deviate from the Newtonian gravitational theory, and timing on them has resulted in the effective verification of the reliability of GR [1].

Radio pulsars are rotation powered, and, therefore, majority of them gradually spin down. Various braking mechanisms, including magnetic dipole radiation, GW radiation, and stellar winds, have been proposed. Each of these mechanisms exhibit different spin evolution behaviors. High-precision braking-index measurements can help us to understand the braking physics of pulsars.

In the new era of GW astronomy, it will become increasingly urgent to establish a new GW window at the frequencies ($\sim$ nHz) by the pulsar timing array (PTA) in the coming years [10, 11]. The European Pulsar Timing Array (EPTA), Parkes Pulsar Timing Array (PPTA), the North American Nanohertz Observatory for GWs (NANOGrav) working individually to advance this area of pulsar timing research, and they also collaborate by establishing the International Pulsar Timing Array (IPTA) to search for GW together. The FAST will definitely play an important role in the development of Chinese Pulsar Timing Array [1)]. In addition to the GW information veiled in the 2nd order correlation of PTA, the 0th and 1st order correlations can be applied to provide time standards and to aid interplanetary/interstellar navigation. PTA can also be used for constructing the ephemeris of the solar system [12].

(3) Pulsar searching

The extremely high sensitivity of the FAST will allow us to search pulsars in the Milky Way and the nearby galaxies. The strong pulsars in M31 is hopeful to be detected [13], which can be subsequently to study the intergalactic medium (IGM). one may also understand the evolution of galaxy with the discovery of sufficient extragalactic pulsars in a galaxy,

It would also be encouraging to discover pulsars with extreme physics. For example, pulsars with ultra high rotating speed provide indicators of pulsar's matter state [14]. A pulsar may be more likely to be a strangeon star than a neutron star if it spins with a sub-millisecond period [15]. Pulsars with strong magnetic fields are interesting, and their observations may contain a wealth of strong field physics. To discover a pulsar below the death-line would also be important, because this would mean that the current pulsar radiation model has to be modified.

Peculiar pulsars are the focus of the searching. A Pulsar/black-hole binary system would be priceless, because it would provide a new test of GW theory and advance the pulsar population research. If a pulsar, on $P - \dot{P}$ diagram, is located between normal pulsars and recycled pulsars, it may provide information about pulsar evolution. If the pulsar was observed to exhibit a large duty-cycle, it could be used to study the polarization and the pulsar magnetic field. New single pulse phenomena may considerably vary and may contain information about the radiation process and the pulsar magnetosphere.

More pulsar samples help with population research. Approximately 3000 pulsars have been discovered to date, however they constitute a very small fraction of the observable pulsars in the Milky Way. If more pulsars are discovered, their evolution can be well studied. With a maximum observable zenith angle of 40° [16], the FAST is expected to detect more than 4000 pulsars [17] of many different forms. The commonalities of each kind of pulsar can be summarized, and the reasons associated with the characteristics of each pulsar can be inferred.

(4) Other related fields

The FAST can be combined with other domestic or overseas telescopes to form a very long baseline interferometry (VLBI) network, which can be used to accurately locate the pulsars. Accurate measurement of the exact position of a pulsar in a binary system, and together with the timing results, one can obtain the complete information about the orbit, and consequently measure pulsar mass.

Currently, fast radio burst (FRB) is very puzzling. It has

1) http://kiaa.pku.edu.cn/news/2017/first-chinese-pulsar-timing-array-meeting-held-kiaa

a pulse signal similar to that of a pulsar, and is generally assumed to be pulsar-originated. It is expected that FAST will able to observe distant FRB events and provide detailed structural information about FRBs.

The FAST can also work in the Search for Extra-Terrestrial Intelligence (SETI) project. The signals from distant space are dispersed by the interstellar medium, and the readability of the signal requires some periodicity or quasi-periodicity. This is similar to the pulsar data, and the algorithm for searching pulsars can be used to perform SETI related work. Besides, pulsars are closely related to extraterrestrial life exploration, and alien mega structures may be found around the nearby pulsars [18] (by the way, it is worth mentioning that the first extrasolar planet was found around a pulsar [19]).

In a word, the FAST can play a very important role in advancing pulsar science. In the coming years, high-quality scientific output on pulsars will be expected during a period of rapid development, which would certainly be essential for us to understand the cosmic laws, from gravitational to strong forces, etc.

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