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Advancing Pulsar Science with the FAST

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The authors discuss potential remarkable achievements for pulsar science with the FAST (pulsar monitoring, timing and searching, as well as others related), and expect a FAST era of pulsar science to come.

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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 (ie., compressed baryonic matter at low temperature). Pulsars are not only testbed for fundamental interactions (e.g., the nature of gravity [1] and of strong force at low-energy scale [2]), but also essential tools to detect nano-Hz gravitational wave [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 focused in this research field.

Pulsars have a very good showing, and have never stopped presenting surprises since the first discovery in 1967, because of advanced facilities. The biggest single-dish radio telescope, Chinese FAST (Five-hundred-meter Aperture Spherical radio Telescope), is going to observe pulsars regularly, with extremely high sensitivity but without complicated data processing for antenna array. The signal-to-noise ratio is $\propto A\sqrt{t}$, with A the effective area and t the observing time, and a 1-minute observation with the FAST can thus be comparable to a 10-hour action with a 60-meter telescope if the same receiver keeps stable for such a long time. Therefore, we could expect a FAST era of pulsar science to come.

In this essay, we are discussing potential remarkable achievements for pulsar science with the FAST: pulsar monitoring, timing and searching, as well as others related.

- Pulsar monitoring

The FAST with high-sensitivity can provide high signal-to-noise ratio data, with subtle and dynamical structure information. This means that it is not always necessary to superimpose the pulses during the analysis, and the change in the pulse sequence between different cycles can be obtained well. New data dimensions (e.g., phase and polarization) beyond frequency will be opened up for more information. In fact, the correlation between multiple sets of data dimensions could open a new window to understand 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 allows these phenomena to be found in more pulsars, and new manifestations of these phenomena can be analyzed [5, 6]. The single-pulse

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phenomenon is related to the physical processes in the pulsar magnetosphere, and studying their performance and statistical properties can help to analyze the radiation mechanism.

Pulsar is a powerful tool for studying interstellar medium. The FAST could provide high precision data to measure the distribution and turbulence of interstellar medium (not only free electrons, but also the atomic gases [7]). In fact, the polarization-calibrated data could also be used to determine the interstellar magnetic fields [8].

The physical environment on the pulsar is extreme, with strong electromagnetic fields, strong gravitational fields, and supranuclear dense matter, to be difficult or intractable to manufacture in terrestrial laboratories. Therefore, understanding the physical processes on the pulsar may help to discover some fundamental points. Because of non-linearity, the physical processes in strong electromagnetic fields are very complex and difficult to calculate with certainty. The non-perturbative quantum chromodynamics associated with the cool dense matter cannot even be theoretically solved. Whereas the pulsar observation data can provide relevant information.

- 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 knowing the matter state and pulsar formation. The conventional neutron star model does not allow pulsar mass to be higher than $\sim$ 2.5 or less than 0.1 times the mass of the sun, but the strangeon star model do [2]. The mass distribution of isolate or binary pulsars can limit the pulsar formation and evolution models.

The general relativity (GR) is thought to be the standard theory for gravity. It is based on the assumption of the strong equivalence principle. However, there is no ab-initial argument to support this hypothesis. The orbits of the compact double pulsar system are seriously deviated from the Newtonian gravitational theory, and timing on them can effectively verify the reliability of the GR [1].

Radio pulsars are rotation powered, and therefore most of them spin down gradually. Various braking medium are proposed, e.g., magnetic dipole radiation, GW radiation, and stellar wind, with different spin evolution behaviors [9]. High-precision brake index measurement can help to understand the braking physics of pulsars.

In the new era of gravitational wave astronomy (GW), it is surely urgent to open a new GW window at the low frequency ($\sim$ 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) are working in great efforts, and they are also collaborated to form the International Pulsar Timing Array (IPTA) to search GW together. While Chinese Pulsar Timing Array is being formed[1)], the FAST will definitely play an important role in the competition. In addition to the GW information veiled in the 2nd order correlation of PTA, the 0th and the 1st order correlation could even be applied for time standard [12] and interplanetary/interstellar navigation, and furthermore, PTA could also be used in constructing the ephemeris of the solar system [13].

- Pulsar searching

The extremely high sensitivity of the FAST allow us to search pulsar in the Galaxy and the nearby galaxies. The strong pulsars in M31 is hopeful to be detected [14], which could be used to study the intergalactic medium (IGM). With more extragalactic pulsars discovered in a galaxy, one may understand better the galaxy's evolution.

It is encouraged to discover pulsars with extreme physics. Pulsars with ultra high rotating speed is an indicator of pulsar's matter state [15]. It is speculated that a pulsar could be likely a strangeon star than a neutron star if it spins with a sub-millisecond period [16]. Pulsars with strong magnetic fields are interesting, and their observations may contain a wealth of strong field physics. To discover a pulsar underneath the death-line is also important, that means the current pulsar radiation model need to be modified.

Peculiar pulsars are also the focus of the searching. Pulsar-black hole binary system is unpriced, which can shine in GW theory test and pulsar population research. If the period and its derivative of pulsar locates between the normal pulsars and the recycled pulsars on $P-\dot{P}$ diagram, it may provide information about pulsar evolution. If the pulsar have large duty-cycle, it could be used to study the polarization and magnetic field. New single pulse phenomena may be various, and they contain information of the radiation process and pulsar magnetosphere.

More pulsar samples help with population research. Around 3000 pulsars have been discovered, but are just a very small fraction of the observable pulsars in the Milky Way. If more pulsars are discovered, then their evolution can be well studied. With a maximum observable zenith angle of 40° [17], the FAST is expected to detect more than 4000 pulsars [18], to be manifested in different forms. The commonality of each kind of pulsars can be summarized, and the cause of the characteristics of each pulsar can be inferred.

- Other fields related

The FAST can be combined with other domestic or overseas telescopes to form a very long baseline interferometry

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

(VLBI) network, which can be used to accurately locate pulsars. Measuring precisely the exact position of the pulsar in the binary system, and together with the timing results, one can obtain the complete information of the orbit, and consequently measure pulsar mass.

Fast radio burst (FRB) is still puzzling now. It has a pulse signal similar to that of pulsar, and is generally thought to be pulsar-originated. It is expected that FAST can observe distant FRB events and give more detailed structure information of FRB.

The FAST can also work in the Search for Extra-Terrestrial Intelligence (SETI) project. Signals from distant space will be dispersed by interstellar medium, and the readability of the signal requires some periodicity or quasi-periodicity. Therefore, this is similar to the pulsar data, and the algorithm for searching pulsar can be used to perform SETI related work. Besides, pulsars are also closely related to extraterrestrial life exploration, alien mega structures may be found around nearby pulsars [19] (by the way, it is worth mentioning that the first extrasolar planet was found around the pulsar [20]).

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

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