Theory and prospects of the pulsar study

Huaichan Liu

High School Affiliated to BIT, Beijing, 100048, China

liuxy@bit.edu.cn

Abstract. After the pulsar was discovered by Hewish, the relevant research has become one of the hottest research fields. Astronomers have noticed that pulsars are of great academic significance in the field of basic scientific research. Due to the large mass and small radius of pulsars, their surface gravitational field is very strong. The existence of general relativity effects cannot be ignored, making pulsars a natural laboratory for the study of strong gravitational fields. the strong magnetic field provides an identical place for the study of radio radiation process, magnetospheric particle acceleration mechanism and high energy radiation. Pulsar as the product of supernova burst after the collapse of massive stars, it is very important for the study of supernova burst theory and understand the formation mechanism of pulsars. In terms of application research, due to the high stability of its rotation period, it has significant applicating prospect in measuring time standard and X-ray pulsar navigation system. The Pulsar has made great remarkable achievements in the past 50 years since its discovery. In short, the discovery and research significance of pulsars are highly anticipated.

Keywords: Pulsar, Black Hole, General Relativity Theory, Dark Matter.

1. Introduction

The pulsar was discovered by Mrs. Jocelyn Bell, a student at the University of Cambridge University fifty years ago. A new radio telescope was built in Cambridge, England, in 1967. Its job is to observe the influence of interplanetary matter done by radio radiation. The entire device cannot be moved, so it can only be scanned one by one by relying on the Sunday movement of each sky zone to enter the telescope's radius. In July 1967, the device was officially put into service with an receive wavelength of 3.7 meters. In the course of her observations, A strange series of pulses which their time intervals are same were found by Miss Bell [1]. She told her mentor Hewish right away, who thought it was caused by some sort of radio wave on Earth. However, the enigmatic pulse signal reappeared the following day at the same hour, also in the same sky zone. This time, it can be demonstrated that the odd signal originates from space rather than Earth. She initially believed it to be a signal from the alien "Little Green Man", but in less than six months, a number of similar pulse signals were found, one after the other. This new class of objects was later proven, and it was given the name pulsars. For the discovery of pulsars, Professor Anthony Hewish received the 1974 Nobel Prize in Physics [2]. The "four great discoveries" of astronomy in the 1960s of the 20th centuries are quasars, cosmic microwave background radiation, and interstellar organic molecules. Pulsars are one of these discoveries. The magnetospheric particle acceleration mechanism, high-energy radiation, and radio radiation processes can all be studied using the pulsar's extremely strong magnetic field. As a product of supernova explosions after massive

DOI: 10.54254/2753-8818/9/20240787

star collapse, pulsars are important for studying supernova explosion theory and understanding the formation mechanism of pulsars [3].

After fifty years of study, people know that pulsars are extremely compact objects from stars evolute to its last phase experiencing supernova explosion which mass between 8 to 25 times sun mass. A neutron star was created when its core material, which contained within 10 times the mass of the sun, collapsed, the density of its material is about a hundred trillion times of the water. The radiation of the pulsar is source of its polar cap which owns strong magnetic field. The neutron star's polar cap will face the earth when it does so, people can observe its radical signal as if receive the pulse signal. The pulsar is seen as the light house at sea. The pulse is observed Whenever the beam of radiation swap through the earth. The pulse’s radius is about 10 kilometers which spins rapidly. Generally, in 1.4 millisecond to 8.5 second [4].

With the discovery of pulsars, China has continued to develop for more than 30 years from backwardness to catching up and surpassing. From the 15-meter radio telescope in 1990 to the "FAST" radio telescope, the largest in the world, in 2016, the observation capability has developed above the world. FAST was completed in 2016 and became the largest radio telescope in the world. So far, more than 3,000 radio pulsars have been discovered around the world for about 50 years, and FAST's observation capabilities will exceed this number.

2. Source

It was postulated in 1968 that pulsars are neutron stars that spin quickly. Strong magnetic fields in neutron stars cause their moving charged particles to generate synchrotron radiation, which then forms a radio beam that revolves around the neutron star. Since a neutron star's rotational axis and magnetic axis often do not coincide, a pulse is detected every time a radio beam passes over Earth [5].

After pulsars are discovered by Hewish, Gold and Pacini proved that they are neutron stars with rapid orbiting speed. As The velocity of its orbiting speed is reducing, the reducing kinetic energy if wasted by radiation. Supernova remnants and young, high-energy pulsars are linked, while young γ-ray pulsars dominated by high-energy radiation gradually evolve into millisecond pulsars due to radiation loss of energy, but the surface magnetic field is not significantly weakened [6].

When a star reaches the conclusion of its evolutionary process, it lacks the fuel for nuclear reactions to continue combusting. As a result, its internal radiation pressure falls, and it eventually collapses under the force of its own gravity. In stars with greater mass, electrons are pressed into the nucleus to form neutrons, at which point the star depends on the degenerate pressure of neutrons to maintain balance with gravity and is a neutron star. Stars with insufficient mass collapse and depend on electron degenerate pressure to fight gravity and become white dwarfs. A typical neutron star is just a few to a few dozen kilometers in radius, but it has a mass that is between one and two times that of the sun, meaning that it has a density of hundreds of millions of tons per cubic centimeter [7]. Because stars retain their angular momentum during collapse, they typically spin up into neutron stars with relatively tiny radii. Additionally, electromagnetic waves can only be released from the location of the magnetic pole because the magnetic axis of the star's magnetic field is typically not parallel to the axis of rotation—some angles can approach 90 degrees—forming a conical radiation region.

By using some of their rotational energy to offset the emitted energy, pulsars eventually slow down their revolution. However, because of how slowly this slowing occurs, atomic clocks' precision cannot always match that of the signal period. The period may be used to determine the age of the pulsar; the younger the pulsar, the shorter the period, see Figure 1 [8].

Pulsars have a very strong magnetic field, electrons are released from the magnetic poles, and the radiation has great directionality in addition to high-speed spinning. The viewer experiences a pulse during rotation when radiation is pointed in their direction because the pulsar's axis of rotation does not

DOI: 10.54254/2753-8818/9/20240787

correspond with its magnetic axis. One thousand pulsars have been found by the year 1999.

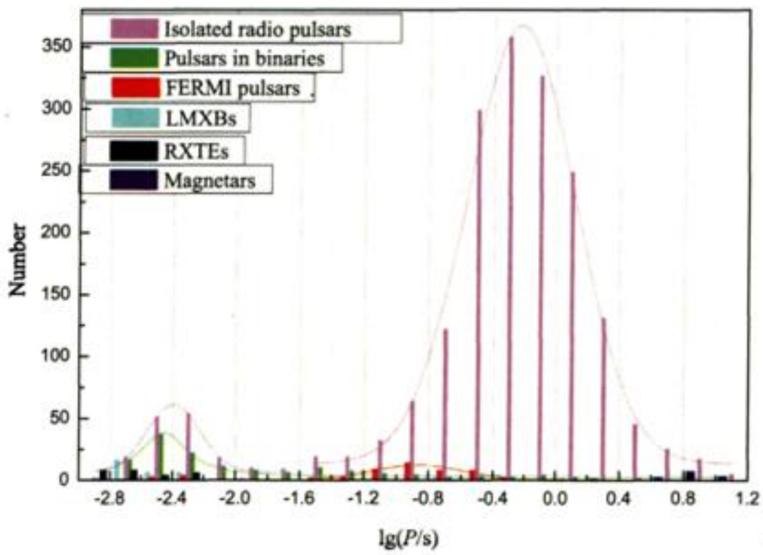

Figure 1. the pulsars' period dispersion. The height of the column in a given interval corresponds to how many pulsars of a certain kind have periods that fall within the interval. The fitted curves of the period distribution for various types of pulsars are represented by colour curves [8].

3. Application

A new astronomical navigation technique is X-ray pulsar navigation, which is reliable and stable, not limited by near-Earth space, but the navigation accuracy is not high during orbital maneuvering. Since pulsars arrive at extremely regular times, gravitational waves change the length of space. Then when gravitational waves pass through the region between Earth and pulsar, the length of the optical path changes, thus changing the pulse arrival time. The foundation for autonomous spacecraft navigation and the use of pulsar clocks as spacecraft time standards is the spatial measurement of X-ray pulsar Pulse Time of Arrival (TOA). The variation law of pulse arrival time with gravitational waves is [9]。

$$\delta t = \alpha \int_0^t \left[h(t_e, \chi_e) - h\left(t_p, \chi_p\right)\right] dt. \tag{1}$$

In terms of pulsar navigation theory, the quality of pulsar signals actually observed by spacecraft is constantly changing due to changes in the space environment. At this time, the TOA accuracy obtained by pulsar data processing is also constantly changing. Therefore, how to ensure that the navigation and positioning algorithm can converge stably and provide stable and reliable navigation services under the changing space environment will be the pulsar navigation theory's next step in development.

The advantages of pulsar navigation are less dependent on ground equipment, and the autonomous navigation and positioning technology does not require continuous support of ground measurement and control systems, which helps to make up for the limitations of traditional navigation methods [10]. Thus, it has attracted more and more attention. Pulsars are known as natural GPS satellites, and the long-term sustainability of their pulse signals is high, comparable to atomic clocks. By utilizing its pulse data, the spacecraft may achieve autonomous navigation, which can significantly reduce the burden of the ground measurement and control system, the number of measurement and control stations, and the cost of the spacecraft's operation management and maintenance. At the same time, pulsars can add orbit fixing and punctuality functions to spacecraft in near-Earth space, solar system and even interstellar travel, to fulfill the continuous high-precision navigation requirements of space missions in various orbits.

After decades of development, X-ray pulsar navigation technology has gradually become matured. With the continuous development of X-ray pulsar navigation theory and the gradual development of space experiments, X-ray pulsar navigation will gradually move towards practical engineering applications and will play a significant part in the exploration of the universe., self-time benchmarking and other fields. Similarly, X-ray pulsar navigation technology faces higher challenges. Based on the computing power constraints of the spaceborne processor in engineering applications and the reliability requirements of actual tasks, efforts are still needed in the computational efficiency of pulsar data processing, the robustness of navigation methods, and the application mode and application scope of navigation. There are lots of method to improve the measurement of TOA.

At present, spacecraft carrying out deep space exploration missions mainly rely on ground measurement and control systems to provide navigation services. The ground measurement and control system's navigation accuracy, however, progressively declines and the delay gradually increases as the distance between the spacecraft and the earth gradually grows. The precision of X-ray pulsar navigation is virtually unaffected by the distance of the spacecraft from the Earth since it is a spacecraft autonomous navigation technology that can deliver navigation services throughout all of space. Therefore, the X-ray pulsar navigation method has an irreplaceable advantage in the field of deep space exploration. For the deep space detector, especially the deep space detector in the cruise section, its running orbit is similar to a straight line, which puts forward high requirements for the observability of the navigation system. Therefore, many methods applicable in near-Earth space such as single X-ray pulsar navigation may no longer be applicable in deep space exploration. In 2008, Graven et al. analyzed the application prospects of X-ray pulsar navigation in sun-horizon point and deep space detection orbit and compared them with the deep space detection network in the United States. The analysis showed that pulsar navigation has more advantages than deep space detection network in space outside 10 AU from Earth. Therefore, the pulsar-based relative navigation approach provides an effective and widely applicable means for deep space detector formation flight.

Using the characteristics of POLAR observation data, the TOA is no longer selected as the observation measurement of pulsar navigation during data processing, but the observation pulse profile is directly analyzed. It can obtain a high-precision forecast orbit in a brief amount of time, and continuously update the orbit parameters by using the long-term stability characteristics of the pulse profile, which can also solve the problem of long-term drift of the orbit model. The Crab pulsar navigation technology verification test based on the POLAR experiment has important application value.

Pulsar-related research contributes to the development of many fields, such as astronomy and space navigation, and the identification of pulsar candidates is an important part of the pulsar search process. However, with the emergence of a new generation of pulsar observation equipment, the number of pulsar candidates produced has also exploded, artificial identification screening can no longer meet the demand, so the machine recognition pulsar method has been produced, but machine recognition still has many problems, so the author on the basis of semi-supervised generative adversarial network proposed two pulsar candidate recognition methods based on semi-supervised learning, semi-supervised learning training method can reduce the great workload for the acquisition of data labels, and effectively solve the shortage of training samples. Problems such as the difficulty of extracting the model. However, some resources are still required, and subsequent research on pulsar candidate identification can be explored in the training method of unsupervised learning, and further reduce the resources consumed by obtaining tags. There are also methods like the fast pulsar positioning and fixing method based on Sparrow Optimization Perception (SSA-QCS) realizes the fast positioning and ensure the velocity of pulsars. SSA-QCS optimizes the quantum measurement matrix by reducing the amount of computation and improving the estimation accuracy.

Attempts to measure gravitational waves with pulsars have been underway for more than three decades. In the radio band, astronomers use large radio telescopes to monitor dozens of millisecond pulsars with very little timing noise for a long time, forming pulsar timing arrays. Due to the differences in observation of sky regions and historical data accumulation, the PTAs selected by different observatories are also slightly different. As a result, there has been cooperation and data sharing among radio astronomy observatories. The addition of FAST now increases the number of pulsars contained in the PTA. At the same time, more sensitive instruments will see a single pulse profile with a higher signal-

DOI: 10.54254/2753-8818/9/20240787

to-noise ratio, which helps increase the sampling frequency of TOA and thus the upper limit of the frequency at which gravitational waves can be detected. Simultaneous monitoring of the same pulsar for longer periods of time reduces the lower limit of gravitational wave detection range. In general, the ever-increasing amount of data in the pulsar timing array increases the significance of gravitational wave signals. At that time, the window of gravitational waves will be further opened to humans.

4. Conclusion

The related research of pulsars has contributed to the development of many fields, such as astronomy and spatial navigation. In this paper, the development history and research prospect of pulsars are discussed and studied. For the structure and evolution of pulsars, the high density can be helpful to the research of many fields, while the navigation research of pulsars as a hot field, there are many ways to solve its defects. Pulsar navigation technology will develop with time, and there will be more efficient pulsar data processing methods, more robust pulsar navigation methods and wider application prospects in the future. As a signal source of stable frequency in deep air, pulsar will be developed into a wider range of application scenarios, while improving the time of arrival accuracy, so as to provide stable navigation services. With the addition of high-sensitivity radio telescopes such as FAST, more undetected pulsars will be found, including previously undiscovered pulsar-black hole systems, and sub-millisecond pulsars, which may be discovered in the future as the accuracy of instruments and equipment improves. At the same time, more sensitive instruments will see a single pulse profile with a higher signal-to-noise ratio, which helps increase the sampling frequency of TOA and thus the upper limit of gravitational wave detection. It is expected that in the near future, new gravitational wave sources can be detected in different ways and the upper limit of each gravitational wave detection can be tightened. At that time, the window of gravitational waves will further unfold for humans. By improving the detection of gravitational waves, the accuracy of pulsar navigation is effectively improved, and pulsar navigation is truly applied to aerospace.

References

[1] Sun, Shouming, Zheng, Wei, & Tang Guojian. (2010). Research on X-ray Pulsars/SINS Integrated Navigation. Chinese Journal of Space Science 30(6), 579-583.
[2] Yang, Tinggao. (2008). Determination of X Ray Pulsar Pulse Time of Arrival at Spacecraft. Chinese Journal of Space Science, 28(4), 330-334.
[3] Zheng, Wei, Wang, Yusong, Jiang, Kun, Wang, Yidi. (2023). Overview of X-ray pulsar-based navigation methods. Acta Aeronauticaet Astronautica Sinica, 44(3), 527451-527451.
[4] Wu, D. L., Liu, J., Wu, J., et al. (2023). Pulsar positioning and velocimetry method based on sparrow search algorithm-optimized quantum CS. Journal of Deep Space Exploration, 10(2), 151-158.
[5] Sun, J C, Zhang, S N, Xiong, S L, et al. (2023). Research progress on polarization measurements of gamma-ray burst prompt emissions and the test of pulsar navigation with POLAR (in Chinese). Chin Sci Bull, 68: 2951–2960.
[6] Lyne, A G, Burgay, M, Kramer, M, et al. (2004). A double-pulsar system: a rare laboratory for relativistic gravity and plasma physics. Science, 303(5661), 1153-1157.
[7] Wu, D L, Liu, J, Wu, J, et al. (2023). Pulsar positioning and velocimetry method based on sparrow search algorithm-optimized quantum CS. Journal of Deep Space Exploration, 10(2), 151-158.
[8] Wu, Xinji. (2000). Luminosity, magnetic field and evolution of pulsars. Amateur Astronomer, 18(2), 10-11.
[9] Yang, Tinggao. (2007). Application of pulsars in space vehicle positioning. Progress in Astronomy, 31(3): 249-261.
[10] Sun, Xiaohui, Han, Jinlin. (2002). Evolution of pulsar magnetic fields. Progress in astronomy, 20(2), 14-18.