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射电脉冲星观测资料及其启示

张 冰 乔国俊
(北京大学地球物理系 北京 100871)

摘 要

在本文中先简要介绍 80 年代以来射电脉冲星方面的观测进展，然后详细介绍射电脉冲星的第一手观测资料，包括空间分布、传播特性、时间特性、脉冲轮廓与偏振以及频谱特性等，并详细综述观测资料向我们提供的信息及给我们的启示，为理论模型的建立和检验提供了基础。

关键词 恒星：中子星 — 脉冲星：一般 — 射电连续辐射：恒星 — 方法：观测

Observational Data and Their Implications of Radio Pulsars

Zhang Bing Qiao Guojun
(*Department of Geophysics, Peking University, Beijing* 100871)

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Abstract

In this paper, the recent observational progress in radio pulsar is briefly introduced. The first-hand observational data of radio pulsars, such as spacial distribution, propagation effects, timing data, pulse profiles, and polarization properties, are reviewed in detail. We also list the implications inferred from these data, which are the foundation to establish and to test the theoretical models.

Key words stars: neutron—pulsars: general—radio continuum: stars—methods: observational

1 Introduction

In 1932, several months after the discovery of neutrons, Landau proposed the concept of a neutron star[1]. Two years later, Baade and Zwicky demonstrated the possibility of forming

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neutron stars in supernova explosion[2]. In 1967, Hewish, Bell et al. discovered the first radio pulsar[3], which is the first celestial body identified to be a neutron star. In fact, the strongest X-ray source Sco X-1 discovered in 1962 by detectors in a rocket, is actually a low mass X-ray binary system with a compact companion of a neutron star, but it was not identified at the time. Later, with the development of observational techniques, especially of space techniques which make astronomy enter the era of whole band one, neutron stars, which belong to one of the three destinations of stars, are proved to exist extensively in our universe. So far, celestial bodies involving neutron stars or neutron star candidates include: radio pulsars, X-ray or γ-ray pulsars with or without radio emission, X-ray pulsars in high mass X-ray binaries (HMXBs), X-ray bursters in low mass X-ray binaries (LMXBs), as well as γ-ray burst sources. Studies on these celestial bodies have greatly enriched our understanding of the properties and features of neutron stars. Among these sources, observational data of radio pulsars are the most full and accurate, and the studies on them are the most deepgoing. Although the amount of published papers in the field has reduced since 1980, people still show special interest in the subject, since not a successful theory is achieved yet to manifest all the observations. In 1993, the Nobel Price of Physics was awarded to Hulse and Taylor for their discovery of the first binary pulsar and the test of general theory of relativity[4]. This is the second time the prize being awarded to the field of pulsar astrophysics. A series of new discoveries in the field since 1980 indicate that it is of vigor and great challenge.

In this paper, we'll review the observational data of radio pulsar and their implications. Section 2 is a brief introduction of recent observational progress. In section 3, the first-hand observational data of radio pulsar are reviewed in detail. In section 4, we'll introduce what observations tell us, which is the foundation to establish theoretical models. Section 5 is the conclusions. As to magnetosphere and radiation theories of radio pulsar, we will review in another paper[5]. Other reviews on pulsar observation and theory can be found in literature [6−10].

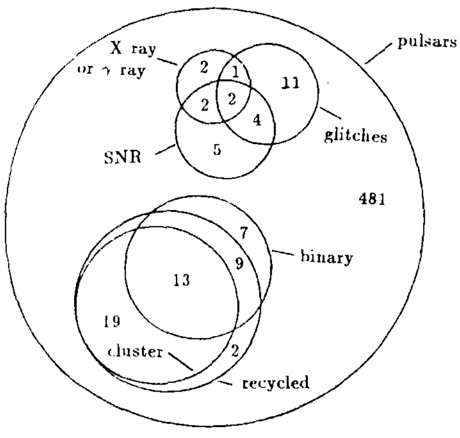

Fig.1 Venn diagram of classification for 558 pulsars[11]

2 Recent Observational Progress, Especially Since 1980

2.1 Total number

The first recent observational advance is the rapid increase of the pulsar population. In the tables by Taylor et al. (1993)[11], the total number of the discovered pulsars is 558, and the recent report shows that the number has reached more than 800, which is 3 to 4 times of the number in the beginning of 1980's. Figure 1 is the classification of 558 pulsars[11].

2.2 Special pulsars

The second observational advance is the

discovery of large quantities of "special" pulsars, including pulsar systems with a companion or planets, millisecond pulsars which have undergone "recycling", pulsars in globular clusters, many new pulsars with high energy emissions (X-ray or γ-ray pulsars), etc. Some important discoveries are listed in Table 1. Here we only give a brief introduction to some important ones. A more detailed review can be found in paper [7].

Table 1 Some important pulsar discoveries

Date Published	Discovery	Authors
1968	Radio pulsars	Hewish, Bell, Pikington, Scott & Collins
1968	Crab pulsar	Staelin & Reifenstein
1969	Crab optical pulses	Cocke, Disney & Taylor
1975	Binary pulsar	Hulse & Taylor
1982	Millisecond pulsar	Backer, Kulkarni, Heiles, Davis & Goss
1987	Pulsar in M28	Lyne, Brinklow, Middleditch, Kulkarni, Backer & Clifton
1988	Eclipsing pulsar	Fruchter, Stinebring & Taylor
1992	B_e/radio pulsar	Johnston, Manchester, Lyne, Bailes, Kaspi, Qiao& D'Amico
1992	planets of pulsar	Walszczan
1992	X, γ-ray pulsar without radio pulse	Halpern & Holt

2.2.1 Non-isolated pulsars

Some pulsars are discovered to have companion(s). The number of binary pulsars is at least 29[11] (recent value: 46). Non-isolated pulsars can be classified according to the mass of the companion(s):

(1) Pulsars with companions of planetary mass: So far, two such systems are discovered. PSR 1257+12 is confirmed to have at least two companions with planetary mass[12]. Studies on the systems may provide us information of formation and evolution of planetary system such as the solar system.

(2) Pulsars with low mass companions (e.g. PSR 1953+29): The companions of these pulsars have mass of $\sim 0.02M_{\odot}$ to $0.4M_{\odot}$, which are usually regarded as white dwarfs[13].

(3) Pulsars with moderate mass companions (e.g. PSR 1913+16): The companions usually have mass of $\sim 1M_{\odot}$, and the systems are usually binary neutron stars[4].

(4) Pulsars with high mass companions: So far, two such systems are found. For example, the companion of PSR 1259-63 is a Be-type star. Such a system is probably a system before accretion driving X-rays are emitted, which might be the progenitor of the binary neutron stars[14].

In pulsar population, four eclipsing binary pulsars are discovered[7], which can provide more information (e.g. pulsar signal absorption or scattering in the companion's wind near the eclipse) of binary systems and thus are very important in pulsar studies.

2.2.2 Millisecond pulsars and pulsars in globular clusters

According to pulsar evolution theory, young pulsars usually have relatively strong surface magnetic fields ($10^{12} - 10^{13}$G) and fast rotation periods (of the order of tens of ms), so they populate in the up-left corner in $\dot{P} - P$ diagram. For old pulsars, on the other hand, periods should be larger, and magnetic fields might be lower. But the first binary pulsar discovered by Hulse and Taylor in 1974 has such a strange feature: rapid rotation period ($P \simeq 59$ms) but weak magnetic field[1]. This is an old pulsar, which populates in down-left corner of $\dot{P} - P$ diagram. Now millisecond pulsars are defined to have periods less than 10ms, and 29 such pulsars are discovered till 1993, among which the fastest pulsar has the period of 1.5ms. The latest data show that 53 pulsars with $P < 25$ms are discovered. These millisecond pulsars are thought to be old pulsars having experienced the "recycling" history due to accretion.

Globular clusters are rich in low mass stars. The high density of the stars enhance the possibility of formation of binaries due to scattering and capturing of the stars. The accreation "recycling" process of these binaries makes millisecond pulsars more likely exist in globular clusters. Searching purposely in globular clusters make a lot of new pulsars discovered. By 1993, altogether 32 pulsars in globular clusters are found, which all have undergone "recycling" process, and 13 of which are binary pulsars[11]. Latest data show that the total number of pulsars in globular clusters has increased to 33.

2.2.3 Pulsars with high energy emission

Pulsar observation data are greatly enriched due to the broad-band observations. So far, 6 γ-ray pulsars and 24 isolated X-ray pulsars are observed. A special pulsar "Geminga" is the only pulsar with optical, X-ray and γ-ray emission but no radio emission at all[15–17].

2.2.4 Other important discoveries

More pulsars associated with supernova remnants (SNRs) (altogether 13 till 1993[11]), more pulsars with interpulses, and some other special pulsars have been discovered since 1980.

2.3 Data accumulating

The third observational advance is that much more detailed observational data are accumulated and analysed. Since 1980, people have gathered large quantities of data of pulsars, such as integrated and individual pulse profiles, sub-pulse properties, polarization features, spectral behaviors, and so forth. These first-hand data are analysed and sorted out, so that some empirical theories are discovered (e.g. a series of work by Rankin since 1983[18–23]). The most important conclusion of these empirical theories is the identification of two distinguish sorts of emission: a "core" emission component in the center of emission beams, and perhaps two hollow "conal" emission components around. The discovery posed a severe challenge to pulsar radiation models. We'll discuss this topic in detail in section 4.

3 First-hand Observational Data of Radio Pulsars

3.1 Spatial distribution

Spatial positions of the pulsars can be measured accurately. Names of pulsars are just on the basis of the celestial and galactic coordinates of pulsars. There are two nomenclatures, namely B1950 and J2000 coordinate systems. For new pulsar discoveries, the International Astronomical Union (IAU) as well as Taylor et al.[11] strongly recommended J2000 system to be used, which is of the form of PSR Jhhmm± ddmm, where hhmm and ddmm denote the right ascension and the declination of the pulsar in the year 2000, respectively. For example, PSR 0531+21 belongs to B system, and it should be PSR J0534+2200 in J system. Using spatial positions and the calculated pulsar distances, full spatial distribution of the known pulsars can be studied. Taylor et al. showed that the observed pulsars are concentrated to the galactic disk, and their distribution shows some evidence of spiral structure of the Galaxy. Most of the observed pulsars are located in the solar neighborhood[11].

3.2 Propagation information

Pulsar radio emission will interact with intersteller media when they propagate from emission region to the earth. Two observational quantities can provide propagation information.

The dispersion measure (DM) is a direct observational quantity representing the differences of time of arrival (TOA) for different frequencies, which can be expressed as

$$\mathrm{DM} = \int n_e \mathrm{d}l = < n_e > d, \tag{1}$$

where $< n_e >$ is the mean number density of the electrons along the light trajectory, and d the distance of the pulsar. So we see DM can be used to estimate pulsar distances.

The rotation measure (RM) is another direct observational quantity representing the degree of Faraday rotation of polarization plane of pulsar emission due to propagation effect, which can be expressed as

$$\mathrm{RM} = 0.81 \int n_e \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{l} \approx 0.81 < B_n > \mathrm{DM}, \tag{2}$$

where $< B_n >$ is the mean interstellar magnetic fields along the light trajectory. Using RM and DM, Han and Qiao analysed the magnetic field distribution and structure of the Galaxy, and came to the conclusion that magnetic field distribution of the Galaxy is in accordance with the spiral structure[24].

3.3 Timing properties

Timing is the most important observational property of pulsar. For all pulsars, we can get precise pulse periods which are in the range of 1.5ms—5.09s. Period derivations $\dot{P}$ for most pulsars (with typical value of $10^{-15}\mathrm{s}\cdot\mathrm{s}^{-1}$) and second order derivations of period $\ddot{P}$ for some pulsars can also be obtained. For binary pulsars, we can even get some other important parameters, such as orbital period P_{ob} and other orbital parameters. Using these timing quantities, we can derive some important parameters of pulsar (see section 4).

Usually the pulsar periods are gradually increasing ($\dot{P} > 0$) due to energy loss, but several pulsars have sudden discontinuous decreases of rotation period, which is known as "glitches". A typical glitch is shown in Fig. 2[8].

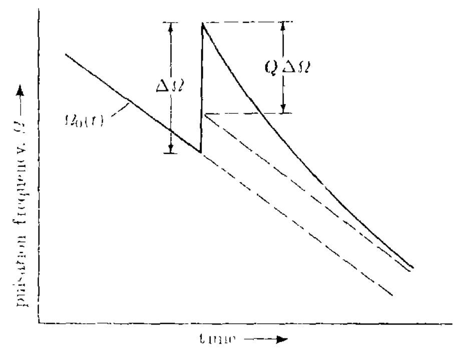

Fig.2 A typical "glitch" phenomenon[8].

3.4 Intensity

The lower limit at present to absolute pulsar radio luminosity seems to be about 10^{25}erg · s^{-1}, whereas the brightest rarely exceed 10^{31}erg · s^{-1}. Since the scale of emission region is very small, the brightness temperatures of pulsars are quite high, which can exceed 10^{28}—10^{30}K. This means the radiation must be coherent. The emission properties are frequency dependent. At a given frequency, the emission profile in a pulse period is called an individual pulse. When time resolution τ of the detector reach 1ms, an individual pulse can be found to be made up of one or more sub-pulses which have widths of $\sim$ 1%—2% of pulsar period.When τ reaches 10μs, some sub-pulses will show microstructures with widths of $\sim$ 0.1% of period. When superposing a sequence of some hundreds of individual pulses, one can obtain a stable pulse profile, namely, the integrated pulse profile, which indicates a window of pulsar emission.

3.4.1 Individual pulses and sub-pulses

An individual pulse is usually composed of one or more sub-pulses. But the position and intensity of the sub-pulses are usually different for different individual pulses. A sub-pulse can randomly appear in any position in the integrated pulse window, and has a Guassian emission beam and almost 100% polarization. So sub-pulses are usually regarded as units of radiation.

There are two important special phenomena of individual and sub-pulses.

The first is the "drifting subpulse" and "modulation" phenomenon. The property of "drifting subpulse" is that the positions of sub-pulses in the integrated pulse profile change orderly, so that sub-pulses drift (see Fig.3)[9]. For these pulsars, successive pulses appear at the fundamental period P_1 (the rotation period P) and the pattern repeats at interval P_3, while sub-pulses are separated by a typical interval P_2. The energy in single pulses depends on the phase of the sub-pulses as they drift across the profile. The pattern of sub-pulses repeats at interval P_3, so that the pulse energy at a given phase is modulated at this periodicity. This is the "modulation" phenomenon.

The second is the "nulling" phenomenon, which indicates that the intensity of an individual pulse can be less than 1% of that of a normal pulse.

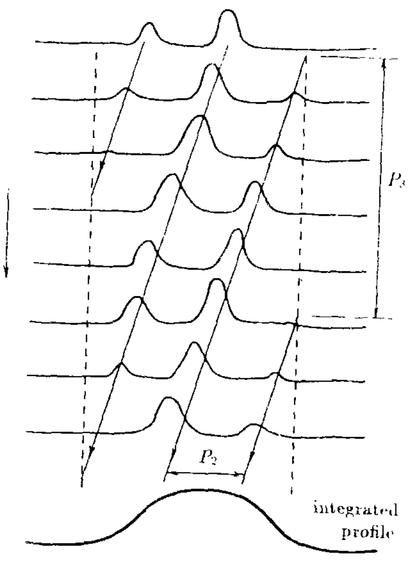

Fig.3 Typical "drifting" sub-pulses[9].

This is an abrupt interruption of emission.

3.4.2 Integrated pulses

Usually, the integrated profiles of pulsar are stable, which usually have more than one components (see section 4 in detail). The widths of profiles to the whole period ratio (the duty cycle) is generally 2% to 10%. Some even have duty cycle greater than 35%, which are called extended pulses, and can be explained by very small inclination angle between the magnetic field axis and the rotation axis. For some pulsars, a second component, known as an "interpulse", appears somewhere near, but not exactly at, the halfway point between the main pulses. This can usually be explained by assuming a perpendicular rotator with the inclination of about 90°. Recently, Manchester argued that most, may be all, "interpulse" emission is emitted from the same source as the "main" pulse[25].

"Mode changing" is a special phenomenon for integrated pulses. In some pulsars, the integrated pulse profiles can abruptly change to a new configuration, the "abnormal mode", for a long sequence of pulses, and then return abruptly back to the original state of "normal mode" (see Fig. 4)[9].

3.5 Polarization

Polarization properties are the most important characteristics of radio pulsars. Sub-pulses of pulsar are usually highly polarized. Integrated pulses have some new polarization features:

(1) Usually the integrated pulses are also highly polarized, but not all of them have such a feature. This is because the polarization property of an integrated pulse is the superposition of many individual ones. If the polarization properties of sub-pulses are stable, and no orthogonal modes exist, this superposition can also result in highly polarized emission, otherwise the polarizability of emission is declined.

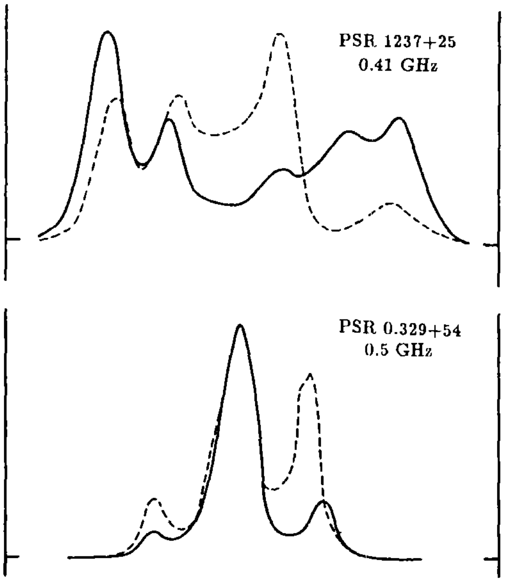

Fig.4 Two pulsars with mode changing features[9].

(2) The position angles of linear polarization usually swing with phase in pattern of "S" or "inverse S". But some pulsars show 90° sudden jump of position angles, which can not be interpreted by hollow-cone beam model. Usually, two non-coherent orthogonal modes in pulsar emission beams are assumed to interpret this abruption behavior.

(3) Circular polarization components exist in some pulsars. A change in sense of circular polarization is frequently observed in the middle of a pulse in some pulsars.

3.6 Spectral behaviors

All above are the properties at a given frequency. An overall understanding of pulsar emission properties relies on multi-band observations. Usually the survey frequency for pulsar is 400MHz. For pulsars near galactic disk, a higher frequency (e.g. 1.5GHz) is often used to lessen the error caused by TOA of different frequencies.

The spectral behaviors include frequency-dependent evolution of various observational quantities, which include the following points.

3.6.1 Spectra

As mentioned above, it is quite difficult to observe a pulsar at higher radio frequencies. So it is quite difficult to obtain with accuracy the spectrum of a pulsar. But for strong pulsars, several spectra have been determined fairly well (see Fig.5)[9]. Generally speaking, pulsar radio spectrum between 100MHz to 2GHz can be regarded as a power law, with spectra indices in the range of −1 to −3, with the average value of −2. For lower frequencies (< 100MHz), there is often a flattering or turnover

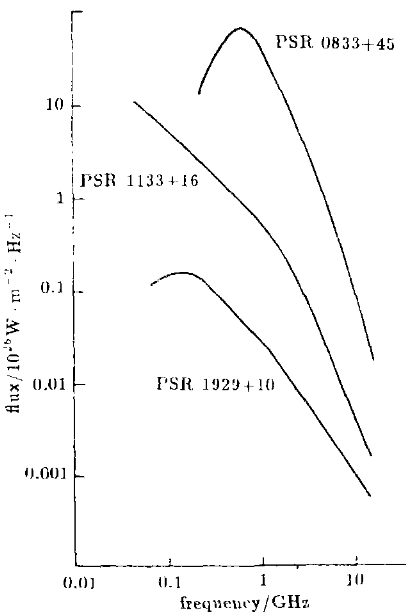

Fig.5 Radio spectra of several pulsars[9].

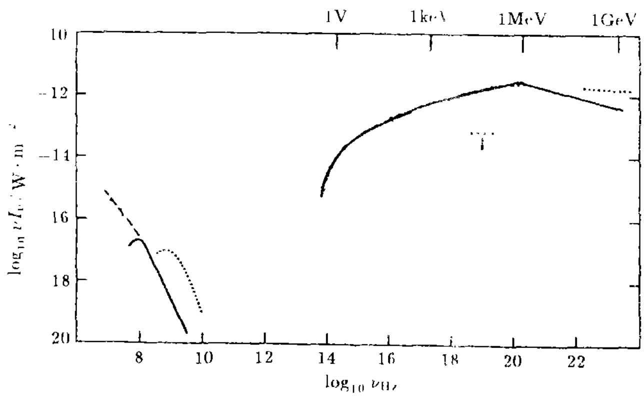

Fig.6 Whole-band spectra of Crab and Vela pulsar[9].

at the low frequency end. For higher frequencies (> 1GHz), the spectrum is steeper. It is quite necessary to emphasize that these observations are of the averaged, or integrated, signal. The apparent simplicity and smoothness of the spectra conceals a more complex behavior in the individual pulses.

Pulsars with high energy emission have more complicated spectra. The whole band spectra of Crab and Vela pulsars are shown in Fig.6[9].

3.6.2 Frequency evolution of the pulse widths

Usually the widths of profiles are defined by half power width W_{50} or 10% power width W_{10}. Generally speaking, the widths become narrower at higher frequencies. But observations show inverse

phenomenon that widths narrower at lower frequencies. This is the so-called "absorption features" (see Fig.7)[19].

3.6.3 Frequency evolution of pulse profiles

Pulse profiles usually vary a lot at different frequencies. Rankin concluded three evolutionary paths[18] which will be discussed in section 4.

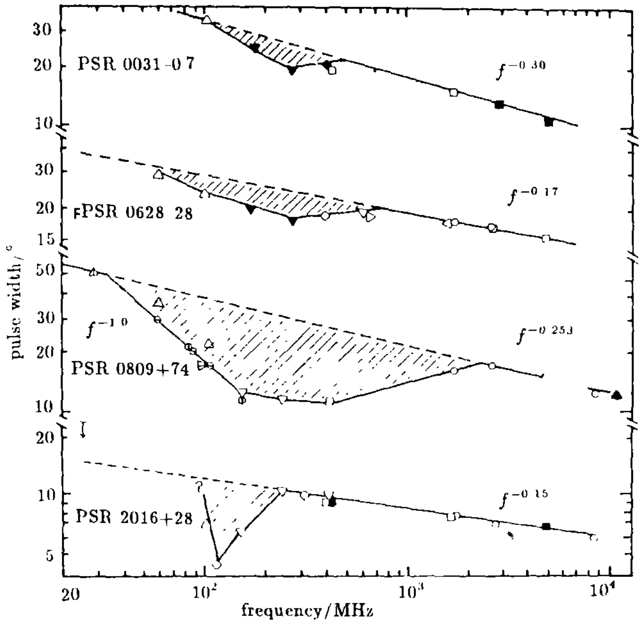

Fig.7 A typical "absorption feature" of spectral behavior of pulse width[19].

4 Information and Implications from the Observations

4.1 Nature of the source

Shortly after the discovery of pulsar, Gold pointed out that the mysterious sources are highly-spinning magnetic neutron stars[26]. Soon, this point of view was generally accepted. We now know the following natures of pulsar.

(1) Pulsars are neutron stars, and the pulse periods are rotating periods. This is because only stars with such small scales as neutron stars can have such short rotational periods. Pulsars are spinning down, and the radiation energy from a pulsar is attributed to the spin-down energy loss.

(2) Very small "duty cycle" of pulsar radiation indicates that pulsar emissions are concen-

trated in a small window. Assuming energy loss rate of a neutron star is equal to magnetic dipolar radiation power of pulsar, we can estimate that most pulsars have very strong surface magnetic fields of the order of 10^{12}G. So pulsars are usually regarded as strongly-magnetized neutron stars with global magnetic fields of a dipole. Plasma in the magnetosphere is "frozen" in field lines, so that a "light cylinder" is defined at the region where co-rotating velocity is equal to the speed of light. The polar cap region within the "last field lines" defined by the light cylinder is just the emission window of pulsar.

(3) Strongly-polarized power-law radio emission infers that the radiation mechanism is non-thermal, and that the radiation is optical-thin. Very high brightness temperature ($T_B \sim 10^{28}$K) indicates that pulsar emission is coherent.

(4) Spatial distribution of pulsar shows concentration to the galactic disk, which indicates that most of them are in the Galaxy.

4.2 Derived quantities from timing parameters

Timing parameters (P, $\dot{P}$ and $\ddot{P}$ for some pulsars) are the most important observational quantities, with which we can derive some most important parameters of pulsar[7].

4.2.1 Spin-down energy loss rate

Pulsar rotation energy is $E_{\rm r} = \frac{1}{2} I \Omega^2$, and the energy loss rate is

$$\dot{E}_{\rm r} = -I\Omega\dot{\Omega} = 4\pi^2 I\dot{P}P^{-3} \approx 4\times 10^{31}({\rm erg\cdot s^{-1}})I_{45}\dot{P}_{-15}P^{-3}, \quad (3)$$

where $\Omega = 2\pi/P$, $\dot{P}_{-15} = \dot{P}/10^{-15}{\rm s\cdot s^{-1}}$, $I_{45} = I/10^{45}{\rm g\cdot cm^2}$. Here $\dot{P} > 0$ is required.

4.2.2 Surface magnetic field

Dipolar radiation power of a neutron star is

$$\dot{E}_\mu = \frac{2}{3c^2}\mu_\perp^2 \Omega^4. \quad (4)$$

where $\mu_\perp = \mu\sin\alpha = B_0 R^3 \sin\alpha$, B_0 is the surface magnetic field of the neutron star, R is the radius, and α is the inclination angle of the neutron star. Assuming $\dot{E}_{\rm r} = \dot{E}_\mu$, we then have

$$B_0 = (\frac{3Ic^3 P\dot{P}}{8\pi^2 R^6})^{1/2} \approx (1.0\times 10^{12}{\rm G})(P\dot{P}_{15})^{1/2}. \quad (5)$$

Here $I = 10^{45}{\rm g\cdot cm^2}$, $R = 10$km are adopted, and $\sin\alpha \approx 1$ is assumed.

4.2.3 Braking index

Supposing

$$\dot{\Omega} = -k\Omega^n, \quad (6)$$

n is called the braking index of the pulsar, so that

$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = 2 - \frac{P\ddot{P}}{\dot{P}^2}. \quad (7)$$

where $\Omega = 2\pi/P$. For dipolar radiation, we have $n = 3$.

4.2.4 Characteristic age

Pulsar age can be estimated by integrating Eq.(6), which is of the form

$$\tau = \frac{P}{(n-1)\dot{P}}, \tag{8}$$

and τ is called the characteristic age of a pulsar. For $n = 3$, we have $\tau = P/2\dot{P}$.

4.2.5 $\dot{P} - P$ diagram

The logarithmic diagram of pulsar $\dot{P}$ and P is an important tool for pulsar studies. Figure 8 is the $\dot{P} - P$ diagram of 447 pulsars following paper [11]. Young pulsars are located in the up-left corner, and then evolve to down-right, transverse across the "death line" and then disappear[27,28]. Recently we proposed two new meaningful lines, the "birth line" and the "appearance line", which can give a clearer picture of pulsar evolution[29,30] (see Fig.8).

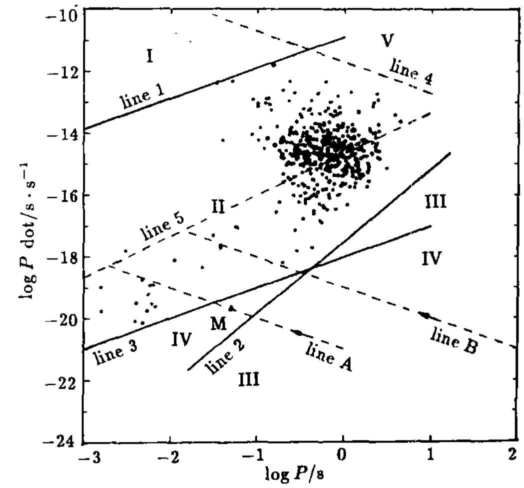

Fig.8 The $\dot{P} - P$ diagram of 447 pulsars. Line 1, 2, 3 are the "birth line", "death line" and "appearance line", respectively[29].

4.3 Information of emission beams inferred from pulse properties

Pulse intensity, polarization and their spectral behaviors are the most detailed data of pulsar observation. It is meaningful to conclude some empirical laws from the first-hand observation data. These laws can bring implications to establish theories and to test them. Rankin called these laws "empirical theories"[18–23]. The important points of these "empirical theories" are to classify pulse profiles, to infer emission beams, and to try to interpret them.

4.3.1 Morphological taxonomy

The earliest work on this topic is the "hollow cone" model (or single vector model) by Radhakrishnan and Cooke[31], which suggests pulsar emission beam is a hollow cone. The model can interpret the double and single profiles by assuming different line-of-sight trajectory. This is a very simple model, and was soon discovered to be incomplete.

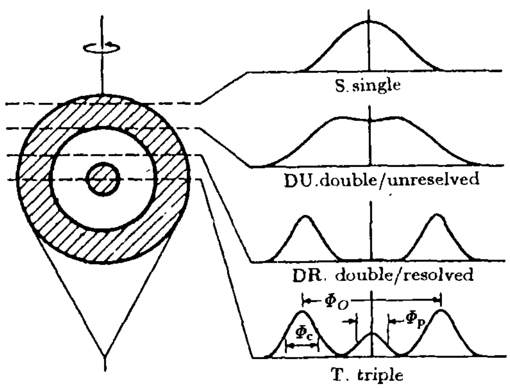

Fig.9 Backer's pencil beam model of pulsar emission beams[31].

Backer posed the "pencil beam" model in 1973[32], which suggests pulsar emission beams are composed of a hollow cone and a pencil beam in the center. Different sight trajectories can result in 4 kinds of pulse profiles: single (S), double unresolved (DU), double resolved (DR), and triple (T) profile (see Fig.9).

Based on the morphological characteristics of polarized average profiles and their formal evolution with radio frequency, Rankin gave a detailed classification of pulse profiles. Five major categories of her taxonomy include core single (S_t), conal single (S_d), double (D), triple (T), and multiple components (M). Besides, there still exist some less important categories such as conal triple (*c*T), one-sided triple ($T_{\frac{1}{2}}$), one-sided double ($D_{\frac{1}{2}}$) and quadripartite profile (Q). From the observations, Rankin inferred the emission beams of pulsars as Fig.10[18,33]. Different categories of pulsar profiles are due to the different line-of-sight trajectories.

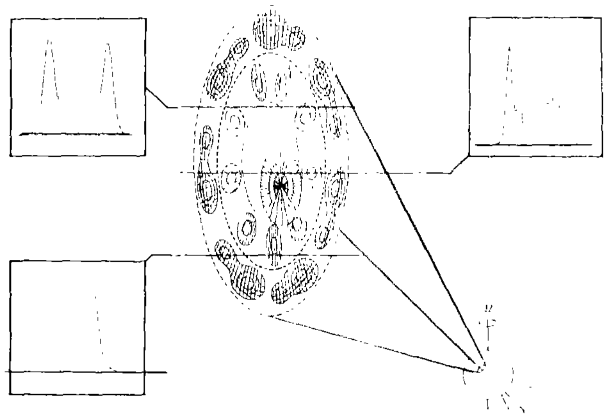

Fig.10 The pulsar emission beams inferred by Rankin[18]

From Fig.10, we can see that there are two distinct physical types of pulsar emission: a "core" emission in the center and perhaps two "conal" emission outriders. According to Runkin[18], the two kinds of emission vary a lot in many aspects.

(1) Core emission tends to have rather steeper spectra than their associated conal outriders.

(2) Core emission region is near neutron star surface, while conal emissions take place at higher height in the magnetosphere.

(3) There is a circular polarization component in core emission, which often changes sense near the center of core profile component. But conal emissions do not share this property.

(4) The linear polarization position angle of core emission often shows abruption behavior, while those of conal emissions only show normal "S" pattern.

(5) Pulsars with core emission component alone are statistically very young, those with both core and conal emissions usually have moderate characteristic ages, while those with conal components alone are usually old ones.

It should be noticed that a seven-component pulsar was discovered recently, which shows the evidence of the existence of a third cone[34].

4.3.2 Spectral behavior of pulse profiles

Different observational frequencies are connected with different emission regions, so that pulse profiles and polarization features can vary a lot. In the hollow cone model, pulse widths are smaller when frequencies are higher. This means the higher the observational frequency, the lower the emission region. This is the "radius-to-frequency mapping".

Using her own classification system and multi-band observation data of many pulsars, Rankin concluded three evolutional "path" of pulse profiles[18]:

$$(\mathrm{T?}) \rightarrow (\mathrm{D}) \rightarrow \mathrm{S_d} \qquad (a)$$

$$\mathrm{S}_t \rightarrow (\mathrm{T}) \begin{cases} \rightarrow \mathrm{D} & (b) \\ \rightarrow \mathrm{M} \rightarrow (\mathrm{Q?}) & (c) \end{cases}$$

where the direction of arrows are towards higher frequencies. Paths (*b*) and (*c*) probably represent more central trajectories of the sight line than (*a*).

The understanding of the three trajectories is based on two properties of emission. One is the concept of "radius-to-frequency mapping", which means that the emission heights decrease when frequencies are higher, so that intervals between double peaks gradually emerge together along the "path" (e.g. $D \rightarrow S_d$). The second point is the fact that core emission has a steeper spectrum, so that core component will disappear at higher frequencies (e.g. T→ D, M→Q), while conal components become less important at lower frequencies (e.g. S_t →T, T→M).

4.3.3 Radius of emission beams

Rankin studied the data of 110 pulsars with core emission and came to two important conclusions[21]:

(1) Pulsar core emissions are emitted near the neutron star surface.

(2) Pulse widths of the core emission are anti-proportional to the period square. For observation frequency of 1GHz, she got

$$W_{\mathrm{core}} = 2^o.45P^{-1/2}/\sin\alpha, \qquad (9)$$

where α is the inclination angle.

Rankin then gave a similar study to 150 pulsars with conal emissions also at 1GHz, and attained relationship of two conal emission radii and periods:

$$\rho_{\mathrm{inner}} = 4^{\circ}.33P^{-0.52}, \qquad (10.1)$$

$$\rho_{\mathrm{outer}} = 5^{o}.75P^{-0.50}. \qquad (10.2)$$

Gil did the similar work at 1.4GHz, and obtained[35]:

$$\rho_{50}^{\mathrm{in}} = (4^{\circ}.15 \pm 0^{\circ}.5) \cdot P^{-0.46\pm0.25}, \qquad (11.1)$$

$$\rho_{50}^{\mathrm{out}} = (5^{\circ}.52 \pm 0^{\circ}.5) \cdot P^{-0.49\pm0.02}, \qquad (11.2)$$

$$\rho_{10}^{\mathrm{in}} = (4^{\circ}.92 \pm 0^{\circ}.5) \cdot P^{-0.48\pm0.03}, \qquad (11.3)$$

$$\rho_{10}^{\mathrm{out}} = (6^{\circ}.33 \pm 0^{\circ}.5) \cdot P^{-0.47\pm0.04}, \qquad (11.4)$$

where ρ_{50} and ρ_{10} are half power width and 10% power width, respectively.

The $\rho - P$ relations have been disputed for a long time. Lyne and Manchester argued that $\rho \propto P^{1/3}$ [36], Kuzmin et al. argued that $\rho \propto P^{1/2}$ [37], while Robert and Sutherland argued that $\rho \propto P^{2/3}$ [38]. The work by Rankin[21,23] and Gil[35] supported the argument of $\rho \propto P^{1/2}$. Recently, Gil and Han used Monto-Carlo method to simulate beam radius according to different models, and compared the results to the observations[39]. The results also support the conclusion of $\rho \propto P^{1/2}$. But another statistic work by Han strongly indicates that $\rho \propto P^{1/3}$ [40].

4.3.4 Altitudes of emission regions

Cordes concluded 5 methods by which emission altitudes may be estimated[41]:

(1) Polar cap model method: This is the most common method to estimate emission altitudes. According to the polar cap model, the radius of emission beam is

$$\rho = \frac{3}{2}(\frac{r_e}{r_c})^{1/2} \approx 2^{o}.49P^{-1/2}(\frac{r_e}{R})^{1/2}(\frac{R}{10\text{km}})^{1/2}, \tag{12}$$

where R is the neutron star radius, r_e the radius of emission region (the distance from emission region to neutron star center), r_c the radius of light cylinder. Assuming the emissions are emitted on the last field lines, comparing empirical relations (9)–(11) with Eq.(12), one can get the altitudes of the emission regions.

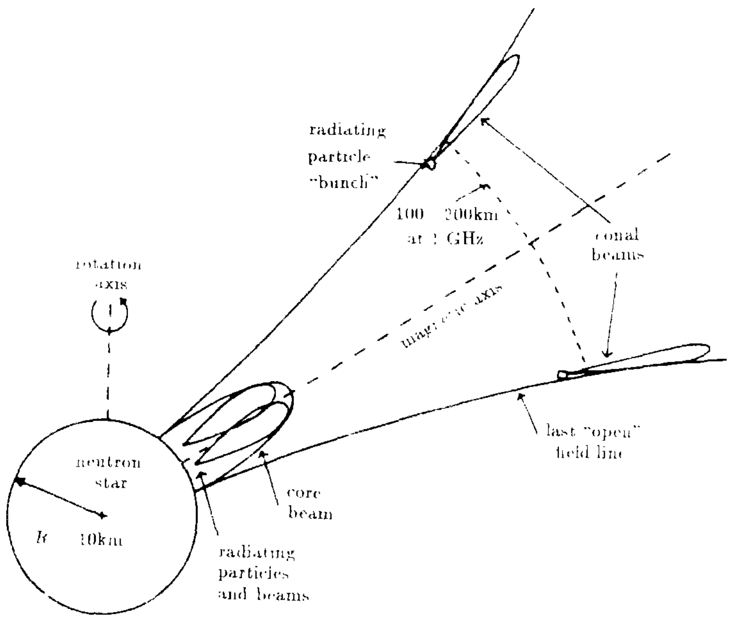

Fig.11 A cartoon of pulsar emission regions inferred by Rankin[32]

Using this method, Rankin presented the following results: The core emission region is near the neutron star surface ($r = R$). For $P = 1$, the emission height of inner cone is about 120km, while that of outer cone is about 210km (see Fig. 11)[33].

(2) TOA – ν method: The time of arrival (TOA) for different frequencies should satisfy the relationship of TOA (ν) $\propto \nu^{-2}$ due to the effect of propagation dispersion. So deviations from the relationship may be due to the different heights of emission regions, which can be used to

estimate emission altitudes. Usually the results are $r_e \leq 0.03r_c$.

(3) v/c effects method: Different emission altitudes have different degree of retardation and twist of field lines. Using this method, the emission heights are estimated to be 100 – 1000km.

(4) Interstellar scintillation (ISS) method: ISS observations can constrain emission altitudes of pulsar. The results are usually $r_e \leq 0.08r_c$.

(5) Space VLBI method: It is possible in the future to observe pulsar emission region using high resolution space VLBI.

The above results indicate that although the precise position of emission region is not determined, it is sure that the region for pulsar radio emission is well within the light cylinder.

4.3.5 Polarization modes

Radhakrishnan and Rankin got following empirical laws after a careful study of pulsar polarization data[22]:

Polarization of conal emission is quite simple. Usually no circular component exists, and the linear polarization position angle swings with phase in "S" or "inverse S" pattern. These features can be well interpreted by the single vector model[31].

The polarization features of core emission can not be interpreted by the single vector model. (1) The linear polarization position angle sometimes shows 90° abruption behavior near the center of pulse profiles. (2) Virtually, all circular polarization is observed in core components, that is, in core-single (S_t) profiles and in the central components of triple (T) and five-component (M) profiles. Two extreme types of circular signature are identified, an antisymmetric type wherein the circular polarization changes sense in midpulse, and a symmetric type wherein it is predominantly of one sense. For the antisymmetric type, circular polarization is strongly correlated with the sense of rotation of the linear position angle. Transitions from positive (left-hand or LH) to negative (right-hand or RH) are found to accompany negative (clockwise) rotations of the position angle, and vice versa[22].

Following implications can be inferred from the polarization data: (1) The "abruption" of linear position angle indicates that the polarization is not a single vector. It is quite possible that there exist two orthogonal modes[22]. The two modes can be either at same altitudes by different mechanisms, or, more likely, be at different altitudes by same mechanism. (2) Circular polarization are usually observed in core emission components. Radhakrishnan and Rankin then supposed that core emission is due to a different mechanism comparing to conal emissions[22]. But Lyne and Manchester argued that radiation should be continuously varied with emission altitudes, so that only one radiation mechanism exists[36]. (3) The symmetric type of circular polarization may originate in propagational effect, while the antisymmetric type may be of geometric origin[22].

4.3.6 Shape of emission beams

Jones pointed out that the emission beams of pulsar are elongated in the latitude direction by a factor of 2.5[42]. Narayan and Vivekanand had the same conclusion and found that beams seem to become more nearly circular in long-period pulsars[43]. Lyne and Manchester argued that the emission beams should be circular[36]. Wu and Shen also suggested that the beams are usually circular, but are elongated slightly in the longitude direction for short period pulsars, while in latitude direction for long period ones[44]. Biggs[45] and Mckinnon[46] also suggested possible slight elongation in longitude direction. Gil and Han's results denied the view of latitudinal elongation, but supported the view of quasi-circular or slight longitudinal elongation[39].

4.3.7 Empirical theories of three special phenomena

Rankin concluded the empirical laws of three special phenomena[20]:

Mode changing occurs in pulsars with triple (T) and multiple (M) profiles which generally exhibit both core and conal components. This means that mode changing is actually a reorganization of core and conal emission. During a mode changing, the intensity of the core components is frequently enhanced in "abnormal" modes, and "abnormal" pattern of conal emission is rather more asymmetric about the core component. Only slight changes of polarization signatures happen during the changing, which infer not strong variation of magnetic field configuration of the emission region. Very young pulsars (S_t) are not found to exhibit mode changing behavior. Most mode changing stars have periods greater than 0.7s and spin-downs less than $10^{-15}s \cdot s^{-1}$, so they are relatively older pulsars.

Drifting subpulse and modulation features are exclusively associated with conal emission. The former happens in pulsars wherein the sight line traverses the conal emission lobe tangentially, while the latter in the case of sight line cutting the conal lobe. The phenomenon means that the emission points of conal emission are drifting orderly.

Nulling is not associated with pulsars S_t with core emission alone, but can be observed in pulsars S_d, D, T, M, etc., which are with conal emission. No simple correlation is found between the null fraction and the period, spin-down, surface magnetic fields, or age of pulsars. All these greatly weakened the suggestion that the stars "die" by "nulling away".

5 Conclusions

As mentioned above, pulsar observational data provide us with much meaningful information. Some empirical laws are found. The information and the laws set a foundation to establish theoretical models, and in the mean time, become important criteria to test the models. So far, not a attentively model is yet achieved to explain all the observational facts. This poses a great challenge to theoretical astrophysicists. Nevertheless, much wonderful work has been done to understand the pulsar mysterious behaviors, which are reviewed in our companion paper[5]. It is believable that people can understand the above mysteries in the near future.

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