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射电脉冲星的磁层与辐射机制理论

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摘 要

在本文中先简介强磁场中一些特殊物理过程的特性，在此基础上综述了射电脉冲星的磁层与辐射机制理论。关于磁层，主要由 GJ 模型出发，从斜转子磁层、加速区机制及回路问题三方面总结前人对磁层问题的认识。关于辐射机制，则侧重于由“相干”问题展开，指出逆康顿散射模型的优势。文末对各种模型作一简单评价。

关 键 词 恒星：中子星 — 脉冲星：一般 — 辐射机制：非热 — 磁场

Theories of Magnetosphere and Radiation Mechanism of Radio Pulsar

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Abstract

In this paper, properties of some special processes in strong magnetic fields are briefly introduced, and the theories on magnetosphere and radiation mechanism of radio pulsar are reviewed. As to the magnetospheric models, we start with the GJ model, and then deal with the three important problems: the oblique rotator, the site and the mechanism of particle acceleration, and the current closure problem. As to the radiation mechanism, we focus on the “coherent problem”, and point out the advantages of the Inverse Compton Scattering model. Some comments on the models are presented in the end.

Key words star: neutron—pulsars: general—radiation mechanism: non-thermal-magnetic fields

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1 Introduction

Shortly after their discovery, pulsars were known to be fast rotating neutron stars[1]. Large quantities of observational data have been accumulated since then, and provided us with a lot of information about pulsar radiation[2]. Although we know why a pulsar pulsates — its rotation, yet the real problem is why it SHINES[3], or what is its radiation mechanism. The understanding of the problem includes four aspects, i.e. (1) the basic physical problem; (2) the global structure of pulsar magnetosphere; (3) the models of radiation region and radiation mechanism; and (4) the observational facts[4].

We have reviewed in detail the observational data of radio pulsars in the companion paper[2]. In Section 2 of this paper, we'll briefly introduce the physical properties near a strongly magnetized neutron star. In Section 3, theories of pulsar magnetosphere are reviewed in detail, especially the formation of the particle acceleration region. In Section 4, we introduce several radiation models, with the emphasis on the Inverse Compton Scattering (ICS) model. Comments on various models are posed in Section 5.

2 Physical Properties near a Strongly Magnetized Neutron Star

As fast-rotating magnetized neutron stars, pulsars have the most important feature of strong magnetic fields, with the typical value of $B \sim 10^{12}G$. The strong magnetic fields make the physical processes in neutron star vicinity have some new properties[5].

2.1 Landau states of the electrons and positrons in strong magnetic fields

In strong magnetic fields, the momentum of the electrons and positrons along field direction is continuous, but the momentum perpendicular to the field direction is quantified, so that electrons and positrons must occupy discrete Landau states with energy

$$E_n = (m^2c^4 + p_z^2c^2 + 2nm^2c^4\frac{B}{B_q})^{1/2}, \tag{1}$$

$$n = l + \frac{1}{2}(s+1) = 0, 1, 2, \dots \quad l = 0, 1, 2, \dots$$

where m, p_z are the mass and the tangent momentum of the particle, respectively. $B_q \equiv m^2c^3/e\hbar = 4.414 \times 10^{13}$G is the critical magnetic field (in which the cyclotron energy of an electron equals to its rest energy), $s = \pm 1$ represent spin-up or spin-down state of the particles, respectively. Notice that for the ground state $n = 0$, only spin-down state exists.

During interaction (collision), transverse momentum is not strictly conserved, because the magnetic fields can absorb or supply momentum. But the parallel momentum and the total energy are strictly conserved.

2.2 Radiation processes in strong magnetic field

In the fields approaching the critical magnetic field, an accurate description of the physics requires quantum electrodynamics (QED). Transition probabilities can be derived from the square of the S-matrix elements. Some calculation results are listed as follows.

2.2.1 Synchrotron radiation and absorption

Classical description of synchrotron radiation neglects the energy levels (the level intervals are too small), hence it has continuous emission spectrum with critical radiation frequency $\gamma^2\omega_B$[6], where $\omega_B = \frac{eB}{mc}$ is the cyclotron frequency, and γ the Lorentz factor of the particles. But this description breaks down in the fields approaching critical field, because the classical critical energy may exceed the electron kinetic energy $(\gamma - 1)mc^2$, when $(B/B_{\rm q})\gamma^2/(\gamma - 1)$ is achieved. Thus we must take into account the discrete Landau levels, so that synchrotron radiation and absorption in strong magnetic fields can be regarded as transitions of electrons and positrons between Landau states, which satisfy the energy and (parallel) momentum conservation conditions

$$E_n - E_{n'} = \hbar\omega, \tag{2}$$

$$P' = P - \frac{\hbar\omega}{c}\cos\theta. \tag{3}$$

Here θ is the pitch angle of the γ-photon with respect to the magnetic field lines.

Harmonics of synchrotron radiation appear at frequencies[7]

$$\omega_{n,n'} = mc^2/\hbar[(1 + 2nB/B_{\rm q})^{1/2} - (1 + 2n'B/B_{\rm q})^{1/2}], \tag{4}$$

for transitions from Landau states n to n'.

Synchrotron absorption is the inverse process of synchrotron radiation. The resonant frequency for absorption to Landau level n is[8]

$$\omega_n = mc^2/\hbar[(1 + 2nB/B_{\rm q}\sin^2\theta)^{1/2} - 1]/\sin^2\theta, \tag{5}$$

where θ is the incident angle of the photons.

An electron or a positron has a certain life time at excited landau levels. The stronger the magnetic fields, the shorter the life time of the particle. In strong magnetic fields near neutron star surface, particles usually populate at their ground states. On the other hand, synchrotron radiation can not access 100% polarization, while pulsars often have highly-polarized radiation. Thus, synchrotron radiation is usually not regarded as the main radiation mechanism of the radio pulsars.

2.2.2 Curvature radiation

Curvature radiation (hereafter CR) is the radiation of the electrons and positrons moving along curved magnetic field lines. It can present high polarization features. In pulsar magnetosphere, electrons and positrons usually only have parallel momentum, so CR becomes an important candidate for pulsar radiation[9].

The total power of CR is[9]

$$P_{\rm cur.} = \frac{2}{3}\gamma^4\frac{e^2c}{\rho^2}, \tag{6}$$

and the critical frequency of radiation is

$$\omega_{\rm c} = \frac{3}{2}\gamma^3\frac{c}{\rho}, \tag{7}$$

where ρ is the curvature radius of the field line, γ the Lorentz factor of the particles, e the charge of electron, and c the light speed.

CR is an attractive candidate for pulsar radio emission. This is because for a particle with energy $E \geq$100MeV (or $\gamma \geq 200$) moving in a dipolar magnetic field ($\rho \sim 10^8 - 10^9$cm), the CR critical frequency falls right in the radio band for pulsar radiation. The highly-polarized feature for CR also matches pulsar radio emission well.

The disadvantage of CR is its very low radiation power

$$f = \frac{P_{\mathrm{cur.}} \cdot \tau}{\gamma mc^2} = \frac{4}{9}\left(\frac{e^2}{\hbar c}\right)\frac{\hbar\omega_{\mathrm{c}}}{mc^2}, \tag{8}$$

where $\tau = \rho/c$ is the characteristic time for particle radiation. When ω_{c} is in radio band ($\omega_{\mathrm{c}} \sim 10^9\mathrm{s}^{-1}$), we have $f \sim 10^{-14} << 1$. So if using CR to interpret pulsar radio emission, one should find a perfect coherent mechanism.

2.2.3 Bremsstrahlung

There are many charged-particles and photons with different frequencies in neutron star vicinity, which interact with each other all the time. Bremsstrahlung is actually the radiation process due to the interaction between the charged particles. The classical bremsstrahlung concerns about the radiation of electrons in the Coulomb field of ions with relatively larger charge of Ze. In pulsar magnetosphere, it is generally accepted that the charges in the magnetosphere are electrons and positrons, so that the cross section of Coulomb scattering is very small. On the other hand, in strong magnetic fields, electrons and positrons are usually "bounded" in field lines, and thus, the possibility of scattering between two electrons at ground states is even smaller. In fact, bremsstrahlung in a magnetic field is really the higher-order process which combines the excitation of an electron by Coulomb scattering with the spontaneous emission of a cyclotron photon[5]. So, Bresstrahlung in strong magnetic fields has a relatively low radiation power, which is usually much smaller than that of synchrotron radiation, and hence, is unimportant in pulsar physics.

2.2.4 Inverse Compton scattering

Inverse Compton scattering (hereafter ICS) is actually the "radiation process" due to interaction between electrons (positrons) and photons. The scattered photons are just the "radiation photons". Herold[10], Lieu[11] and some other authors calculated the scattering matrix elements of Compton scattering (special case for ICS, $\gamma = 1$) using QED method, and obtained the expressions of cross section of Compton scattering in strong magnetic fields. The results show that there exist some resonant frequencies, at which the scattering cross section enhances tremendously. The physics is, when an incident photon has the energy equal to the Landau level intervals of the electron (positron), it will be much easier absorbed by the electron (positron). The electron (positron) is thus excited to higher levels, stays at the state for a very short time, and soon jumps back to the ground state, again. This is just the observed resonant Compton scattering process.

Xia et al.[12] did Lorentz transformation to Herold's results[10], and for the first time presented the numerical calculation of ICS cross section in strong magnetic fields. Figure 1 shows their numerical results, which also show resonant peaks for ICS cross section. For the ground state, the resonant frequency is approximately

$$\omega_{\text{res}} = \frac{\omega_B}{\gamma(1-\beta\cos\theta)}, \tag{9}$$

where $\omega_B = eB/mc$ is the cyclotron frequency of the electron in the magnetic field B. Dermer[13] introduced an approximate analytic method to deal with the ICS process in strong magnetic fields under the assumption of non-relativistic scattering and not too strong magnetic fields. Recently Lin[14] redid Lorentz transformation using Lieu's results[11], and got detailed numerical solutions of ICS cross section.

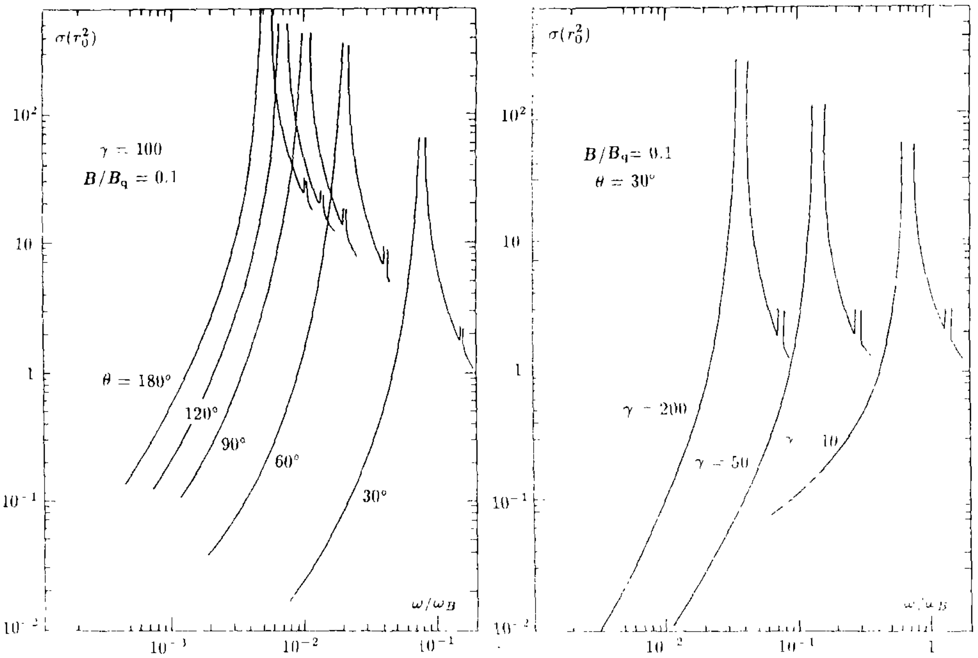

Fig.1 Total cross section for ICS in strong magnetic field calculated by Xia et al.[12] The cross section is in unit of Thomson cross section and the frequency is in unit of cyclotron frequency.

(*a*) The incident angle dependence of cross section, for given magnetic field B and Lorentz factor γ.

(*b*) The Lorentz factor dependence of cross section, for given B and incident angle of the photons.

2.3 Pair production and annihilation

These are some processes for conversion between material and radiation. In eyes of quantum field theory, these processes are just the same as the radiation processes discussed above. We discussed them separately, just because of their importance in pulsar magnetosphere.

2.3.1 One-photon pair production

In a photon field, transitions between a high-energy γ-photon and the "virtual" pairs take place all the time. The process can not become a real one just because conversions of both energy and momentum can not be satisfied simultaneously. But in the existence of a perpendicular magnetic field component, the conversions of both total energy and the parallel momentum can be satisfied, so that real electron-positron pairs come into existence. The necessary condition for the process is:

$$\hbar\omega \cdot \sin\theta \geq 2mc^2, \tag{10}$$

where θ is the pitch angle of the photon with respect to the field lines. Erber[15] presented the attenuation coefficient for a photon of energy $\hbar\omega$ propagating at right angle to the static magnetic field B

$$\alpha(\chi) = \frac{1}{2}\left(\frac{e^2}{\hbar c}\right)\left(\frac{mc}{\hbar}\right)\frac{B}{B_{\rm q}}T(\chi), \tag{11}$$

where $\chi \equiv \frac{\hbar\omega}{2mc^2} \cdot \frac{B}{B_{\rm q}}$, and

$$T(\chi) \simeq \begin{cases} 0.46\exp(-4/3\chi), & \chi << 1 \\ 0.60\chi^{-1/3}. & \chi >> 1 \end{cases} \tag{12}$$

Daugherty and Lerche[16] pointed out that electric fields also play the role of absorbing γ-photons. They derived an equation involving both magnetic and electric fields, and argued that the impact of electric fields in pulsar magnetosphere can not be neglected.

2.3.2 Two-photon pair production

In strong magnetic fields, the two-photon pair production process can also satisfy the conversion condition of both energy and momentum. The necessary condition is[17]:

$$(\hbar\omega_1 \sin\theta_1 + \hbar\omega_2 \sin\theta_2)^2 + 2\hbar\omega_1 \cdot \hbar\omega_2[1 - \cos(\theta_1 - \theta_2)] \geq (2mc^2)^2, \tag{13}$$

where θ_1, θ_2 are the pitch angles of the two photons with respect to the field lines.

The relative importance of the two processes discussed above depends on concrete conditions. Burns and Harding[18] pointed out that one-photon process is more important in the condition of photon density $n_\gamma \leq 10^{25}\mathrm{cm}^{-3}$, and magnetic field $B \geq 10^{12}\mathrm{G}$.

2.3.3 Pair annihilation

One-photon annihilation and two-photon annihilation are inverse processes of one-photon production and two-photon production, respectively. For a detailed discussion, see paper [17].

3 Theories on Pulsar Magnetosphere

In some papers[19] around the discovery of pulsar, it was believed that no magnetosphere exists in the vicinity of a neutron star. This is because the height of the magnetosphere is very low, if one suppose an equilibrium of the thermal energy and the gravitational energy of a test particle. But this idea is wrong, because the electromagnelc force is not taken into account. Goldreich and Julian[20] first proposed a "static" magnetospheric model of an aligned rotator by involving the effect of electromagnetic force (GJ model), which lays the foundation of the study of pulsar magnetosphere and is regarded as the "standard" magnetospheric model ever since. But it is just an ideal model. A realistic model should solve the following problems: (1) What does the magnetosphere look like for an oblique rotator? (2) Where is the accelerating region of the particles in pulsar magnetosphere, and how is it formed? (3) How does the global current of magnetosphere form a circuit? The solution of these questions will come to a self-consistent solution of pulsar magnetosphere, but such a theory has not been obtained yet up to now. Nevertheless, people have got a deep understanding to pulsar magnetosphere, which is introduced as follows.

3.1 GJ model

The basic assumptions of GJ model include: (1) the neutron star is an aligned rotator ($\frac{\partial}{\partial\phi}=0$); (2) the currents along field lines within light cylinder are neglected ($\frac{\partial}{\partial t}=0$); and (3) the particles co-rotate with the magnetosphere. The following conclusions are reached:

(1) A rotating magnetic neutron star cannot be surrounded by a vacuum. The Lorentz force acting on a particle in the neutron star interior should be zero, so that

$$\boldsymbol{E}+\frac{\boldsymbol{\Omega}\times\boldsymbol{r}}{c}\times\boldsymbol{B}=0. \tag{14}$$

Neglecting inertia of the particles, the particles near the neutron star surface should also satisfy Eq.(14). But if the star were surrounded by a vacuum, the condition would break down, so that a parallel electric force would pull electrons and ions off the surface to fill the magnetosphere.

(2) The magnetosphere is charge-separated (see Fig.2). A quasi-static solution $\boldsymbol{E}\cdot\boldsymbol{B}\sim 0$ is obtained, so that the charge density in the magnetosphere is

$$\rho_{\mathrm{e}}=-\frac{\boldsymbol{\Omega}\cdot\boldsymbol{B}}{2\pi c}\cdot\frac{1}{1-(\Omega r\sin\theta)^2/c^2}=-\frac{\boldsymbol{\Omega}\cdot\boldsymbol{\mu}}{2\pi c}\cdot\frac{1}{r^3}(3\cos^2\theta-1), \tag{15}$$

where μ is magnetic torque of the neutron star. The circular cone $\cos\theta=\pm1/\sqrt{3}$ is the zero charge surface or null surface, which separates two regions with different charges.

(3) GJ also discussed the circuit closure problem. They found three zones: "the near zone" within the light cylinder, "the wind zone" outside the light cylinder and the "boundary zone" near the expansion shell of the supernova remnant. They argued that the circuit closes in the "boundary zone". But the discussion is rather simple. The real valuable work of GJ model is the first two conclusions mentioned above.

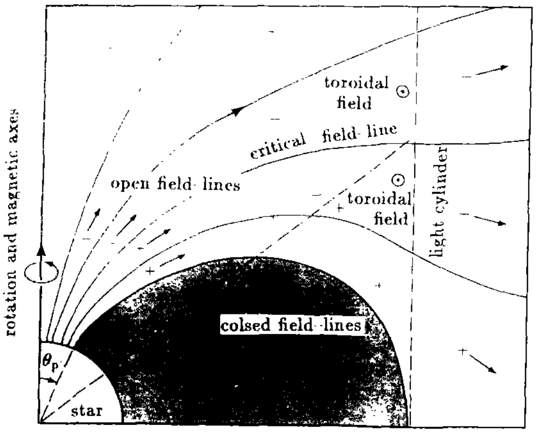

Fig.2 Charge and current distribution in GJ magnetosphere. The figure is for a case that the magnetic axis is parallel to the rotation axis[20].

3.2 Magnetospheric models of an oblique rotator

Shortly after GJ model, Goldreich[21] himself supposed that the oblique rotator have just the same physics as an aligned rotator, and that the obliquity served only to sweep this beam around to give pulsed radio emission. This led to the so-called "lantern effect". Mestel[22] carefully studied the magnetospheric structure of a neutron star with magnetic axis perpendicular to the rotation axis, and pointed out that the conclusions of GJ is still sound: the particles will also be pulled out from the surface to fill the magnetosphere. Henriksen and Norton[23] also studied the magnetosphere of a perpendicular rotator under the force-free condition, and pointed out that there is a sharp point at the connection point of a field line and the light cylinder. They called the point "neutral point" (see Fig.3). Cheng, Ho and Ruderman[24] (CHR) introduced the charge distributions and the possible circuit distributions of a quasi-static oblique rotator (see Fig.4).

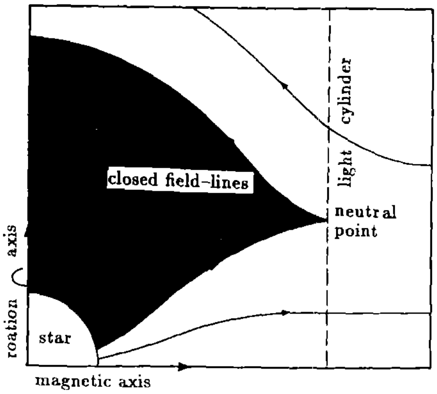

Fig.3 Magnetosphere structure of a perpendicular rotator by Henriksen and Norton[23].

The discussions above do not include the particle flows and the acceleration mechanisms. Arons[25,26] et al. presented a detailed study of an oblique rotator and tried to answer these questions. Their magnetospheric structure for an oblique rotator is shown in Fig.5, which will be introduced in detail next.

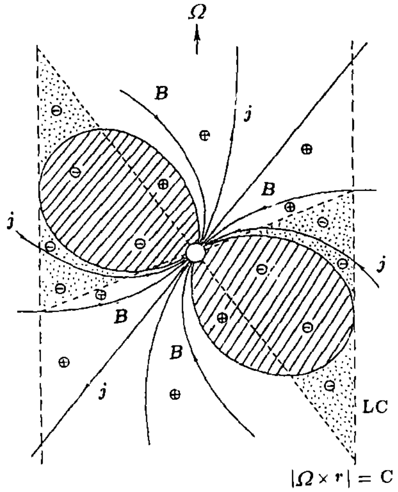

Fig.4 Charge and current distribution for a oblique rotator in CHR model[24].

3.3 Particle acceleration region in pulsar magnetosphere

It can be inferred from the pulsar radiation that there must be a lot of high energy particles flowing out in the magnetosphere, which indicates the existence of a region with none-zero parallel electric field ($\boldsymbol{E} \cdot \boldsymbol{B} \neq 0$). But where is this acceleration region? How is it formed?

In a GJ magnetosphere, $\boldsymbol{E} \cdot \boldsymbol{B} = 0$ is satisfied everywhere, so that a stable charge density distribution is formed (see Eq.(15)). A particle acceleration region requires a deviation from GJ charge density ρ_e. There are two kinds of deviations. One is to form a region with $\rho = 0$, so that the deviation from ρ_e can be attained and be maintained for a long time. This stable acceleration region is called a "gap". Another kind of deviation is called the "space-charge-limited flow" mechanism. The acceleration region is not necessarily stable, but is formed due to charge flows in the magnetosphere. Following are the detailed discussions.

3.3.1 Gap acceleration regions

(1) Inner gap

Ruderman and Sutherland[27] proposed the first gap model in 1975, which is called inner gap model or RS model. The basic idea and main results of the model are as follows.

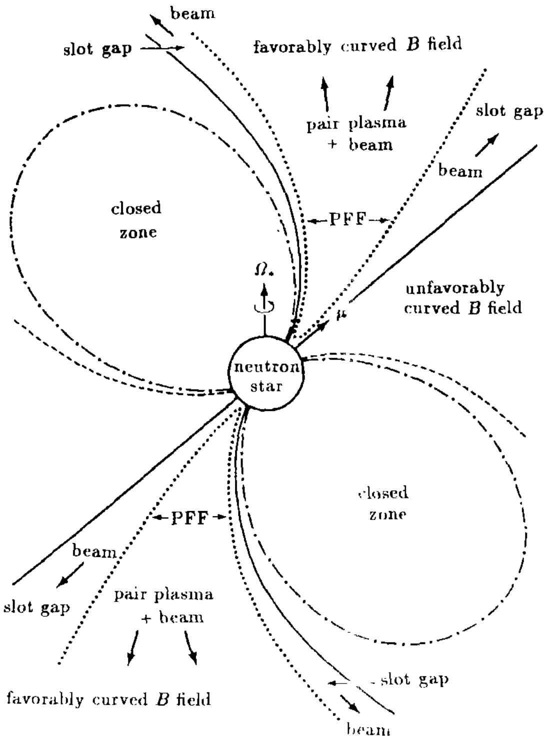

Fig.5 Magnetospheric structure in the slot gap model by Arons[26].

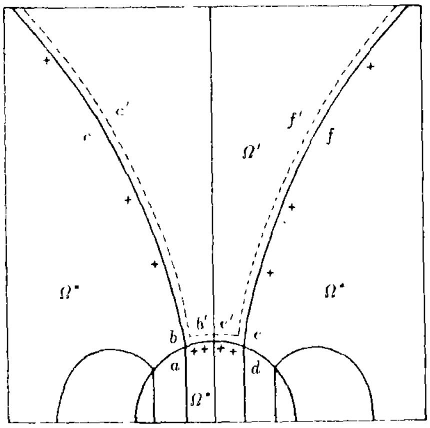

Fig.6 Inner gap in RS model[27].

For GJ magnetosphere with magnetic axis anti-parallel to the rotation axis, the positive particles in the polar cap region have a tendency to flow out. Supposing a close circuit is formed somewhere in the magnetosphere, these positive charges then flow out. But in strong magnetic fields, long molecular chains are supposed to be formed with the ions distributed in a one-dimensional lattice along the chain and with outer sheath of electrons. If the ion binding energy in the neutron star surface is large enough, so that the positive ions are bound in the star surface lattice while electrons can freely flow out, a vacuum gap in the polar cap region can then be formed, namely, inner gap (see Fig.6). RS presented a strict electrodynamical solution of the inner gap structure. For the approximation that the gap height is much smaller than the polar cap radius, the potential drop across the gap can be expressed as

$$\Delta V = \frac{\Omega B}{c} h^2, \tag{16}$$

where Ω is the angular velocity of the neutron star, B the surface magnetic field, h the gap height, and c the light speed. The inner gap grows up with the speed of light, so that the gap potential as well as the parallel electric field in the gap increase quickly. In the mean time, some galactic background photons in the gap will split into pairs in strong magnetic fields in the gap. Once these pairs are formed, they will be accelerated to different directions in the parallel electric field in the gap, and soon attain very high energy ($\gamma \sim 10^6$). These high energy electrons and positrons, in turn, emit γ-photons due to CR process, which will split into pairs again. This process repeats again and again, so that a pair production "avalanche" takes place, and the gap disappears. Before long, the gap grows again, and again disappears. The "sparking" takes place on and on, so that large quantities of particles are spurted into the magnetosphere in bunches. The coherent CR by the secondary particles then causes the observed pulsar radio emission. The gap height in RS model is

$$h \simeq (5 \times 10^3)\mathrm{cm} \rho_6^{2/7} P^{3/7} B_{12}^{-4/7}, \tag{17}$$

and the potential across the gap is

$$\Delta V \simeq (1.6 \times 10^{12})\mathrm{V} B_{12}^{-1/7} P^{-1/7} \rho_6^{4/7}, \tag{18}$$

where B_{12} is the pulsar surface magnetic fields in unit of 10^{12}G, P the rotation period in unit of second, and ρ_6 the curvature of the field line in unit of 10^6cm. In RS model, the multipole magnetic fields are assumed in the vicinity of a neutron star so that usually $\rho \sim 10^6$cm is adopted.

RS model is a relatively successful model. In theoretical aspect, the model presents a natural acceleration region. Radiation is independent of the existence of the circuit in the model. This greatly weakens the circuit closure problem of the magnetosphere. On the other hand, since the secondary pairs are neutral, the difficulty of a charge traveling through the region of opposite charge is avoided. In observational aspect, RS model can explain some observational phenomena, such as the double structure of emission profile, the "S" shape of polarization position angle, drifting sub-pulses, pulsar "death line", etc. Furthermore, the "user friendly" feature of RS model is not shared by other models[28]. The model is concise but reasonable, so it finds favor in many authors' eyes.

But RS model also faces great difficulties. The first one is the "binding energy difficulty". Some calculation results after RS showed that the binding energy of Fe ion in neutron star surface is not that high as RS's previous expectations, but is about one order smaller ($\sim$ 1keV)[29–31]. The large quantities of in-flowing particles due to gap sparking will hit the surface and thus further reduce the binding energy of the ions. Under these conditions, the above-mentioned $\sim 10^{12}$V gap potential will produce too strong a parallel electric field, so that the positive ions will be pulled out from the surface. Thus no gap can be formed. The second problem is the so-called "ICS difficulty". It is known that there is a thermal photon field near a neutron star surface[32–36].

This makes the ICS process of the high energy particles in the gap off the thermal photons not a negligible process. Xia et al.[12] pointed out that the electrons can not be accelerated to $\gamma \sim 10^6$ due to ICS mechanism. Recently, we reinvestigated the sparking process of the inner gap by taking ICS process into account[37], and found that ICS process plays two roles in inner gap physics. One is that ICS is an effective energy loss mechanism of the particles in pulsar magnetosphere. The other is that the up-scattered γ photons due to ICS are more energetic than the CR photons, so that they will induce pair cascade earlier than the CR photons. Thus, gap properties, such as potential drop, gap height as well as the Lorentz factor of the escaping particles can vary a lot from the RS gap. According to our results, the gap potential is much smaller, so that the parallel electric field $E_{\parallel}$ is also smaller. This greatly weakened the "binding energy difficulty". We then studied the $\dot{P} - P$ diagram of the pulsars, re-calculated the "death line", and obtained two new lines, the "birth line" and the "appearance line"[38,39]. The theoretical results are in great accordance with the observations. We also examined the condition of gap formation for different case, and found three modes for pulsar inner gap[40], namely, the "thermal-peak ICS mode", the "resonant ICS mode" and the "CR mode". It was found that the two ICS modes usually dominate the gap sparking process for merely all pulsar population, and that the observed mode-changing phenomenon of some pulsars can interpreted naturally as the switching between the "resonant ICS mode" and the "thermal ICS mode". It is worthy to note that Chen and Ruderman[41] also re-studied the "death line" using RS model. But a consistent result requires some additional assumptions, e.g. the magnetic field configuration, etc.

(2) Slot gap

Arons and his colleagues[42,43,25,44,26] argued that the ion binding energy in neutron star surface can be neglected, so that the inner gap does not exist at all. A series of paper of them calculated the acceleration potential and pair production conditions in polar cap region using the concept of space-charge-limited flow, and obtained the magnetospheric structure as Fig.5. We see a "slot" vacuum gap in the figure, where particles can be freely accelerated. Their detailed

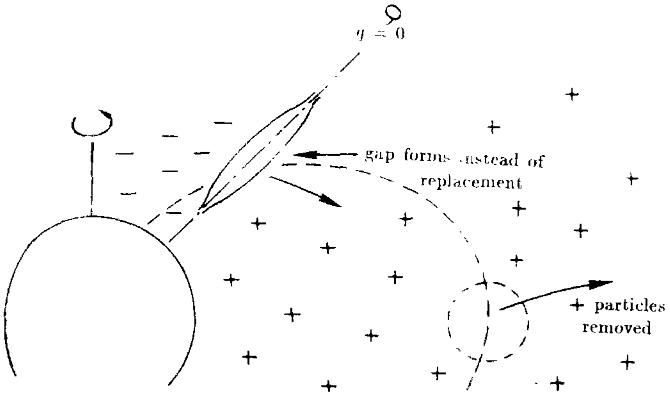

Fig.7 Holloway's outer gap[75].

work are reviewed in detail next.

(3) Outer gap

Holloway[45] first pointed out that, completely filling the volume about the star with a stationary (corotating) charge distribution is not that sound as it seemed at first. If some of the positive equatorial charges were to be removed, there is no way to accelerate new positive charges from the polar regions without first driving all the negative charges back to the surface. He then argued that the system would respond by forming a vacuum gap at the null surface (see fig.7). Cheng, Ruderman and Sutherland[46] improved the model later. But now the prevalent outer gap usually refers the model proposed by Cheng, Ho and Ruderman (CHR model)[24,47].

The basic idea of CHR model is, flows of charge-separated plasma along "open" field lines are incompatible with static GJ magnetosphere charge distributions (see Eq.(15)), unless there is a creation of plasma within the magnetosphere. For a rotating neutron star, assuming global current flow patterns, large regions between the null surface and the light cylinder may likely become charge depleted. But if the regions become vacuum, the strong electric field along the field lines will then accelerate particles to high energies and emit γ-photons in the mean time. These photons may undergo one-photon or two-photon pair production processes, so that a large number of pairs will be spurted into the region to fill the vacuum. Only those regions where pairs can not fill in remain charge depleted. For fast rotating pulsars, this charge-depleted region can then be formed, namely, outer gap. The outer gap is limited on one side by a charge layer on the boundary of the closed field line region and on the other by a charge layer on a surface of 'open' magnetic field lines. The starboard end of the gap is near the null surface, but no outer termination exist within the light cylinder (see Fig.8). Particles can be freely accelerated in the outer gap and emit high energy radiation of the pulsars. Since two kinds of charges are accelerated along different direction, a certain observer can simultaneously receive emissions from two big fan emission beams (see 1, 3 in Fig.8). The observed phase separation between double pulses is determined by the flight path difference between the two beams, aberration of the emitted beam direction, and magnetic field line bending near the light cylinder because of retardation or plasma loading or both. The theory can successfully interpret the high energy emission from Crab, Vela and some other γ-ray pulsars.

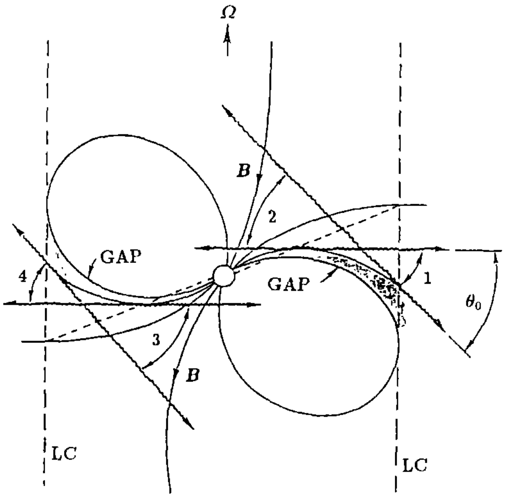

Fig.8 Outer gap in CHR model[24].

3.3.2 "Space-charge-limited flow" acceleration mechanism

The "space-charge-limited flow" mechanism comes from a classical problem in vacuum tube technique, which means that the circuits are limited by the space charges[48,49].

(1) Oscillation current pattern by Sturrock

Sturrock[50] is the first person to use space-charge-limited flow to study the acceleration mechanism of particles in pulsar magnetosphere. He is also the first to introduce the concept of pair production cascade to pulsar studies. He argued that for a rotating neutron star, the regions of open field lines outside the light cylinder can not satisfy the force-free condition, so that current flows must exist in the magnetosphere (Note that he has actually assumed the circuit is closed). The flows of charges then make space charge density deviated from the GJ density, so that a parallel electric field is induced, which can be calculated by solving Poisson equation in the co-rotating frame. The accelerated charged particles then emit CR γ photons that split into pairs soon in strong curved magnetic fields. The positrons then accelerated inward, so that the parallel electric fields disappear and the currents are quenched. Before long, the flows start again due to rotation of the star, and above process happens again. The currents are formed and quenched on and on, so that a picture of oscillation current pattern exists in pulsar magnetosphere, which can induce the "two-flow instability" and result in coherent CR radiation. Sturrock established the foundation of pulsar studies, and his model is regarded as the first "modern model" of pulsar. The RS model is actually the development of Sturrock's work. But it is a pity that his Poisson equation in the corotating frame

$$\nabla \cdot \boldsymbol{E} = 4\pi\rho \tag{19}$$

is incorrect, because the charge density in the frame should rather be the difference of the actual value and the quasi-static value (GJ density) $\rho - \rho_0$ rather than ρ itself. So his estimated accelerating potential is too large.

(2) Stable current pattern by Arons et al.

Fawley, Arons and Scharlemann (1977)[42] first pointed out Sturrock's mistake, and used

$$\nabla \cdot \boldsymbol{E} = 4\pi(\rho - \rho_0) \tag{20}$$

to calculate the parallel electric fields. Under the assumption of zero ion binding energy in neutron star surface so that particles can flow out freely from the surface, they solved the Maxwell equations in the co-rotating frame to find the stable solution of the currents (They actually also assumed the existence of the closed circuit in the magnetosphere.) Neglecting the curvature of the field lines (the case in neutron star vicinity), a stable solution of current in an aligned rotator can be found. Scharlemann, Arons and Fawley (1978)[43] presented a general discussion involving the field line curvatures, and found that a stable solution of space-charge-limited flow current can exist for a perpendicular rotator, but not for an aligned one. Thus they argued that, for a common case of a oblique rotator, the polar cap region with field lines curved towards the rotation axis has a similar configuration as a perpendicular rotator, so that these lines are called the "favorably" curved field lines. Those lines curved away from the rotation axis are more like the field lines of an aligned rotator, thus are called "unfavorably" curved lines. Stable currents may exist in the "favorably" lines, and pulsar radio emission just comes out from this region.

The above-mentioned work only studied the accelerating potential and the current distributions above the pulsar polar cap, but did not discuss the process of pair production. So in these papers the boundary condition of $E_{\|} \to 0$ for $r \to \infty$ is used, which means that the particles can be accelerated in any height in the open field line region of the magnetosphere. Later Arons and Scharlemann (1979)[25], Arons (1981, 1983)[44,26] studied the pair production process, and proposed that there is a pair formation front (PFF) at a certain height above the polar cap region, above which the accelerating potential almost vanishes. The acceleration region locates in the region between the PFF and the neutron star surface, which is called a "diode" acceleration region. The region is just like an inner gap, except that the current in the "diode" is stable, while the inner gap is continuously breaking down, so that the current in the gap is pulsed. On the other hand, calculation results show that the PFF bends upwards towards the magnetic axis and the last field line, where photons can not be absorbed by the magnetic fields. This is the "slot gap" (see Fig.5, Fig.9), where pulsar emission takes place. But Arons did not describe the detailed radiation process and the possible emission beams.

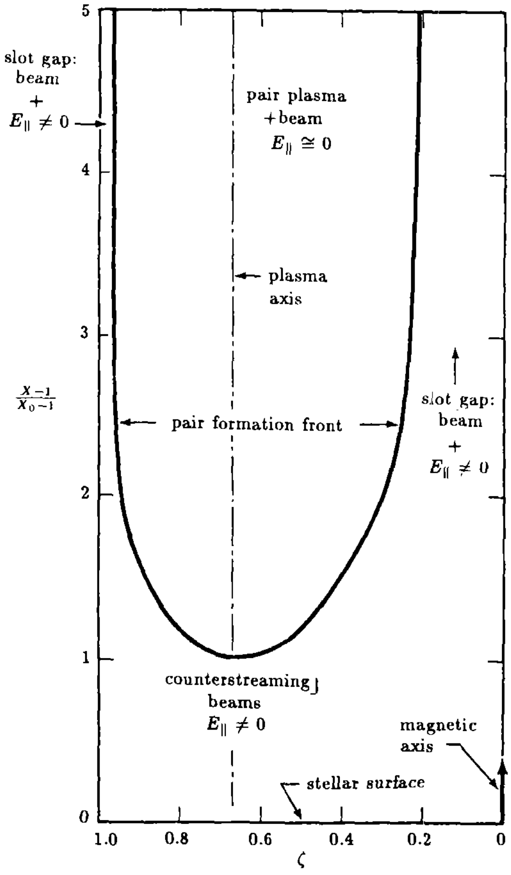

Fig.9 Pair formation front (PFF) and slot gap in Arons' model[26].

3.4 Current closure models

Except the RS model, the above-mentioned acceleration models have a common feature: the assumption of the currents in the magnetosphere. It seems that the existence of these currents is obvious, since the "homopolar induction effect" of highly-spin neutron star can result in great potential difference for different points on neutron star surface, which presents a power source of magnetospheric currents. But the existence of currents also implies another assumption: the currents are closed somewhere inside or outside the magnetosphere. Although the RS model does not depend on the existence of currents directly, the formation of the gap also requires a closed circuit, otherwise the positive charges in the polar cap region can not be pumped out. But how can circuits be closed? Here are some models on the current closure problem.

3.4.1 Disk model

Michel[51,52] deemed that the region outside the magnetosphere of a radio pulsar should not be vacuum, but should rather have a disk like the X-ray pulsars. The only difference is that the accretion to this disk is quite weak. The price of the assumption is to add a source to be confirmed, but can present a natural self-consistent solution for current closure problem, since currents can return to neutron star surface through the disk. But it is doubted that whether such a disk can be formed shortly after the supernova explosion and whether it can be maintained. The model does not present convinced proof by the observations, and the disks have not yet observed till now. So the model does not become the main trend of pulsar theoretical studies.

3.4.2 Wind model

Mestel and Wang[53,54] proposed a current flow by a steady pulsar wind that has particles of both signs streaming away from the star. Just beyond the light cylinder, particles extracted from the poles become highly relativistic and emit high-energy γ-rays. The radiation dissipation in a current sheet then causes electrons to migrate across the field lines toward the equator where they are driven back to the star. The lack of observed γ-rays from most pulsars has been raised as an objection to this model.

3.4.3 Grain model

Cheng [55] proposed that the closed currents are due to high speed proper motion of the pulsars. When a pulsar move rapidly in the space, ablation and ionization of interstellar grains within the magnetosphere may produce the conduction path needed for pulsar operation. In the model, currents are closed within the light cylinder. The model can explain the observed correlation of pulsar transverse speed with $(P\dot{P})^{1/2}$ which is proportion to the surface magnetic field of the pulsar. A higher motion speed produces a larger grain capture rate and, hence, a larger current flow in the star. The increased current, in turn, increases the braking torque on the star and produces the observed correlation.

4 Radiation Mechanism of Pulsar Padio Emission

The site for pulsar radio emission has been argued to be outside the light cylinder[56], at the light cylinder[57], or in the closed field line region[58], etc. But now, the generally accepted knowledge is that the pulsar radio emission comes from the place not far away from the neutron star surface in the open field line region[59,27,26,50].

But there is no consensus so far on the radiation mechanism of pulsar, because pulsar radio emission is not closely related to any of the more familiar radio emission mechanisms in astrophysics[60]. The dominant feature of pulsar radio emission is the high brightness temperature of radiation, e.g. 10^{26}–10^{31}K[60], which means the radiation mechanism must be non-thermal and the radiation must be strongly coherent. We know that the power source of pulsar radiation comes from its dipolar radiation[61,62], but how is this low-frequency large-amplitude wave changed into the observed coherent radio emission? This is where the question is.

The so-called "coherent radiation" is not well defined. A working definition is that coherent emission is any nonthermal emission that cannot be explained in terms of incoherent emission, while later is defined as spontaneous emission of energetic particles when the corresponding absorption process is unimportant, i.e., $k_{\rm B}T_{\rm B} \ll \epsilon$, where $T_{\rm B}$ is the brightness temperature of radiation, ϵ the energy of the particle, and $k_{\rm B}$ the Boltzman's constant[60]. So the dominant feature of the coherent radiation is the significance of the brightness temperature. The coherent mechanism in astrophysics can be classified as maser mechanism, reactive instabilities, and emission by bunches, etc[60].

Melrose[60] reviewed three possible coherent mechanisms of pulsar radio emission. The ICS model posed by Qiao[63,64] is another convincing model.

4.1 Coherent curvature radiation by bunching mechanism

Coherent CR was the first radiation mechanism considered for pulsar radio emission[50,27,65]. According to the model, a bunch of relativistic electrons (or positrons) are bunched in the scale smaller than the wavelengths of the emission photons, and thus emit CR photons in phase. The N particles in a bunch can emit N^2 times the power per individual particle. Note that the bunching mechanism is not necessarily caused by CR. This idea is the earliest mechanism proposed, but it was not improved much later. This is due to two fundamental difficulties of the model: (1) No detailed theory for a bunching instability exists for the case where the velocity dispersion is nonzero. Once the particle velocities are dispersed, the bunching mechanism will be destroyed. (2) No perfect mechanism is posed to explain the formation of the bunches.

4.2 Relativistic plasma emission

An ultimate study of pulsar magnetosphere should involve physical properties of plasma in the magnetosphere, and the collective emission of relativistic plasma is an important process. The process is a multistage one, including the generation of "plasma turbulence" and a partial conversion of energy in this plasma turbulence into escaping radiation which is coherent. The most detailed model so far in this aspect is the one by Beskin, Gurevich and Istomin (BGI model)[66]. Important ingredients in this model include: (1) a plasma response function that incorporates the inhomogeneity associated with the curved magnetic field, (2) a curvature-driven reactive instability in an Alfvén-type drift mode whose existence depends on this inhomogeneity, and (3) the conversion to escaping radiation due to one of several possible conversion mechanisms including relevant nonlinear processes in the relativistic plasma. A notable feature of BGI model is that it allows the escaping radiation to be in either of the two natural high frequency modes of the plasma, which provides a possibility to understand two kinds of pulsar emission, namely, "core" and "conal" emission. The authors of BGI model declared that their model can explain almost all the observational properties of radio pulsar, so the model is of great competitiveness. But the model proposed some unfamiliar but disputable concepts, so it should be a long time before the model is finally accepted or abandoned.

4.3 Linear acceleration emission

When an oscillating parallel electric field in the direction of magnetic field line exists, the charged particles will be accelerated and can emit coherent radio emission. This is the linear acceleration emission or free electron maser emission mechanism. Rowe[67] presented a detailed analysis on the mechanism. The advantage of the model is that it is a direct maser mechanism and can also distinguish the two kinds of emission, but the weakness is that no viable mechanism has been proposed for the required large amplitude electrostatic waves.

4.4 Inverse Compton scattering model

The ICS model posed by Qiao (1988)[63,64] is a new point of view to understand pulsar radio emission. It not only can presents a natural explanation to the high brightness temperature of the pulsar radio emission, but can also interpret many other observational phenomena, such as one "core" and two "cones" for emission beams, spectral behavior of pulse profiles, and polarization properties, etc.

The basic assumptions of ICS model include: (1) pulsar magnetic field is a strict dipolar, (2) a continuously breaking-down inner gap exists which can result in low frequency wave with $\omega \sim 10^5 - 10^6 \mathrm{s}^{-1}$ and high energy escaping particles with $\gamma \sim 10^2 - 10^4$, (3) the low frequency wave can propagate in pulsar magnetosphere due to non-linear effects. Under above assumptions, pulsar radio emission can be explained in term, of the ICS process of the escaping particles from the gap or the secondary pairs off the low frequency wave, since the radiation is optical thin.

4.4.1 ICS model can interpret the high brightness temperature of the pulsar radiation better

As mentioned above, the pulsar radio emission shows very high brightness temperature, so that it is believed to be "coherent". The key of the problem is how to produce such a strong emission power in the observing band. A bunching mechanism is necessary for CR process, because the emission power of a single particle for CR is too low. But for ICS process, the emission power of a single particle is much larger. An estimation shows[63,64]

$$\frac{P_{\mathrm{CR}}}{P_{\mathrm{ICS}}} \sim 10^{-14} \cdot \frac{1}{\alpha_1}, \tag{20}$$

where α_1 is a parameter of the order of unity but less than unity. We can see that the ICS process is a much more efficient radiation mechanism than the CR process, so that we can come to high radiation power for pulsar radio emission in terms of ICS process even without the bunching mechanism.

4.4.2 ICS model can interpret many observed phenomenon naturally

Based on a simple geometry (see Fig.10[68]), ICS model can present a frequency to open angle diagram using the equation of ICS frequency as well as a convincing assumption of γ factor decreasing relation with respect to the emission height[68] (see Fig.11). From the figure, we see that the theory can present the pulsar emission beams with a core and two conal emission components, so that a uniform interpretation is achieved for two kinds of radiation. According to the model, the three components of radiation are emitted at different heights[69,70,39], which is consistent with the results inferred by the observations[2]. The model has interpreted or can interpret the "absorption feature" of pulsar widths[64], the spectral behavior of emission pulse profiles[68], impact of aberration and retardation effect to the shape of emission beams[70,71,39], abruption jump of position angle of the linear polarization[72], and the circular polarization, etc.

4.4.3 Future work

Though the ICS model has shown great potential, there still exist some problems to be further investigated. These include: the concrete mechanism of the propagation of the low-frequency wave, the polarization properties of the ICS process for a single particle and their superposition (i.e. the collecting effect or the "coherent problem"), etc.

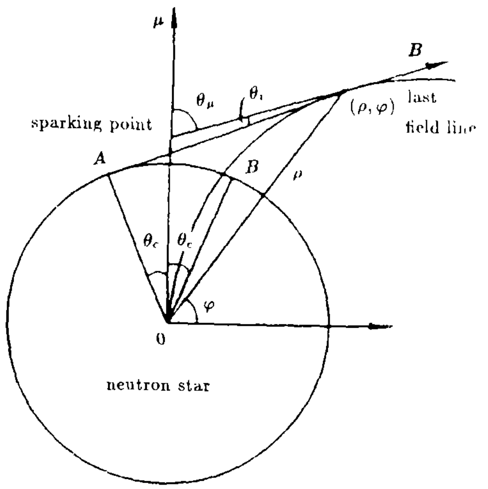

Fig.10 Geometry in ICS model[68].

5 Comments on the Models

From the review above, we see that people have come to a rather deep knowledge of pulsar, but not a model can solve all problems. Some models deal with the magnetospheric problems, while some others with the radiation mechanism. Some are concentrated on the theoretical problems, while some focus on the comparison with the observations. No absolute judgement can be achieved. But we can still evaluate the models under a certain criterion.

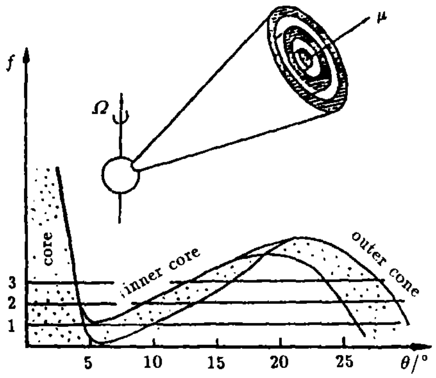

Fig.11 Frequency to open angle relation in ICS model. It is shown that one core and two conal emission components exist in pulsar emission beams. One can observe single, double, triple or multiple pulse profile at a given frequency[68].

1. Some models (e.g. wind model, grain model) only aimed to solve a concrete problem of the pulsar magnetosphere (e.g. current closure problem), so that they are only significant for the certain problem.

2. The most important work for self-consistent solution of pulsar global features includes the slot gap model by Arons and the disk model by Michel, while the former provides the most detailed calculations, and comes to a deep understanding of pulsar magnetosphere. The weakness of the model is that it tried to obtain a strict physical solution, but neglected comparing with the observations. The slot gap model did not present good results consistent with the observations.

3. The RS model can be divided into two parts: the inner gap theory about the accelerating region in magnetosphere, and the bunching CR model for coherent radio emission. The inner gap model is quite concise and practical. Although it faced with the binding energy crisis, using ICS mechanism in inner gap theory has greatly weakened the crisis. We believe that the inner gap

model will still be in people's good graces for a long time in the future.

4. As to the radiation models, RS's bunching CR model is not good to deal with the "coherent" problem. BGI's model is better. ICS model can interpret the high brightness temperature naturally.

5. Being tested by the observations, the RS model can only provide a hollow cone emission, while can not explain the core emission. So far, the models trying to understand the core emission include the BGI's model, the WWC's model[73,74], the linear acceleration model and the ICS model. The BGI's model and the ICS model can interpret many observational properties, while the latter is superior due to its concise physical ideas and good consistency with the observational facts.

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