A Physical Model of Pulsars as Gravitational Shielding and Oscillating Neutron Stars

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Pulsars are thought to be fast rotating neutron stars, synchronously emitting periodic Dirac-delta-shape radio-frequency pulses and Lorentzian-shape oscillating X-rays. The acceleration of charged particles along the magnetic field lines of neutron stars above the magnetic poles that deviate from the rotating axis initiates coherent beams of radio emissions, which are viewed as pulses of radiation whenever the magnetic poles sweep the viewers. However, the conventional lighthouse model of pulsars is only conceptual. The mechanism through which particles are accelerated to produce coherent beams is still not fully understood. The process for periodically oscillating X-rays to emit from hot spots at the inner edge of accretion disks remains a mystery. In addition, a lack of reflecting X-rays of the pulsar by the Crab Nebula in the OFF phase does not support the lighthouse model as expected. In this study, we develop a physical model of pulsars to quantitatively interpret the emission characteristics of pulsars, in accordance with the author's well-developed five-dimensional fully covariant Kaluza-Klein gravitational shielding theory and the physics of thermal and accelerating charged particle radiation. The results obtained from this study indicate that, with the significant gravitational shielding by scalar field, a neutron star nonlinearly oscillates and produces synchronous periodically Dirac-delta-shape radio-frequency pulses (emitted by the oscillating or accelerating charged particles) as well as periodically Lorentzian-shape oscillating X-rays (as the thermal radiation of neutron stars whose temperature varies due to the oscillation). This physical model of pulsars broadens our understanding of neutron stars and develops an innovative mechanism to model the emissions of pulsars.

1 Introduction

Neutron stars are extremely compact objects, resulting from supernova explosions of dying massive stars with 8 to 20 solar masses. The theoretical prediction for the existence of neutron stars in nature was proposed eight decades ago [1]. But the observational discovery of these compact objects was only done in the middle of the 1960s from the measurement of an unusual Dirac-delta-shape pulse-like radio emission from the Crab Nebula [2,3] first observed by Chinese astronomers in 1054. The mass and radius of neutron stars are mostly around 1.4 solar masses and 10 to 20 km, respectively. The recent measurement for the Shapiro delay of light from a binary millisecond pulsar has discovered a neutron star with a mass of about two solar masses [4]; and other measurements have found the radii of some neutron stars to be less than 10 km [5–7]. The mass-radius relation of these unusual neutron stars has been modeled recently by [8].

The conventional interpretation for the observed Dirac-delta-shape pulse-like radio emission was based on the lighthouse model of pulsars as fast rotating neutron stars [9–12]. Figure 1 sketches a diagram for the lighthouse model of pulsars. Charged particles that are accelerated along the magnetic field lines of neutron stars above the magnetic poles produce or give off coherent beams of radio emissions, through mechanisms which are, however, not yet entirely understood. These beams are viewed as pulsing radio-frequency radiation

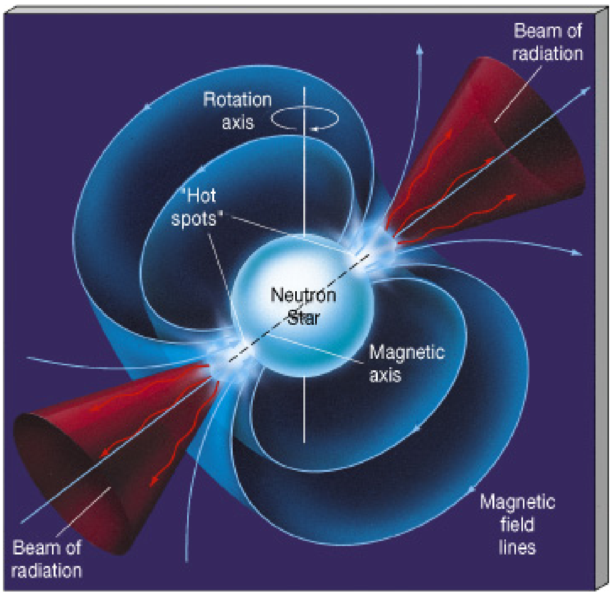

Fig. 1: A sketched diagram for the lighthouse model of pulsars as fast rotating neutron stars (Credit: www.pas.rochester.edu/afrank/A105). Charged particles, accelerated by the magnetism of the neutron star, flow along the magnetic field lines, producing radio radiation that beams outward.

Fig. 2: A flashlight beam through the air (Credit: www.youtube.com/watch?v=ggr5YQYqD0I). One can see the beam, even if it does not point to the viewer, because the air reflects the beam of the flashlight.

when the magnetic poles sweep the viewers. Twenty years after the discovery of neutron stars, quasi-periodic oscillations (QPOs) of X-rays were observed first from white dwarfs and then from neutron stars [13–14]. The recent observations of pulsar PSR B0943+10 by combining the X-ray telescope XMM-Newton and the radio telescope LOFAR have shown that this pulsar synchronously emits periodic Dirac-delta-shape pulses of radio-frequency radiation and Lorentzian shape oscillating X-rays [15]. At present, pulsar quasi-periodically oscillating X-rays are believed to come from inner edges of the accretion disks of white dwarfs, neutron stars, and black holes, but the physical cause still remains unsolved and a detailed consistent theory of how these fascinating stars work remains elusive.

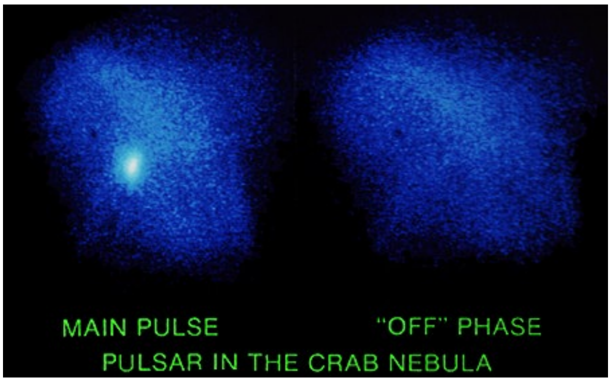

Fig. 3: X-ray images of the Crab Nebula. The left panel is the case when the pulsar turns on and the right panel is the case when the pulsar turns off. When the beam of X-rays points away, why we cannot see the radiation beam formed by the nebula reflection (Einstein Observatory image, Smithsonian Institution Photo No. 80-16234).

It is well known or experienced that a beam of flashlight is visible from the side because part of the light is scattered by the tiny particles like dust in the air (Figure 2). A beam of radio waves can bend or change the direction of propagation due to ionospheric reflections and refractions. However, the similar case does not happen for the beam of emissions (including radio waves through gamma rays) from the pulsar in the Crab Nebula. In visible light, the Crab Nebula consists largely of filaments with ionized gases of temperature $\sim$ 10 – 100 times higher than ionosphere and density $\sim$ 1 – 1000 times lower than ionosphere. The Crab Nebula, though behaving unlike the air or ionosphere, should be able to reflect or scatter the beams of radio waves or X-rays from the pulsar. But the observations have not shown such events occurring when the pulsar is in the OFF phase (see the right image of Figure 3). Figure 3 shows the X-ray images of the Crab Nebula taken by the Einstein Observatory when the pulsar is in the ON (the left panel) and OFF (the right panel) phases. According to the lighthouse model, the ON phase of the pulsar refers to the beam of radiation pointing to the Earth or the viewer; while the OFF phase refers to the beam of radiation pointing to other directions. The X-ray image of the entire Crab Nebula in the ON phase is significantly brighter than that in the OFF phase, especially the region above the lighting pulsar. This indicates that the Crab Nebula does reflect/scatter some X-rays of the pulsar when the pulsar is ON. However, there is not any reflection/scattering happened and perceived when the beam points to other directions through the Nebula in the OFF phase. This fact strongly implies that our conventional lighthouse model may not work. The lack of reflecting/scattering X-rays of the pulsar by the Crab Nebula in the OFF phase does not support the lighthouse model as expected. In the OFF phase, the pulsar is more likely to turn the radiation off entirely rather than just to direct the radiation away from the Earth or the viewer. In addition, the lighthouse model may not be able to theoretically form, except for when the deviation of the rotating axis from the magnetic poles is negligible, a stable accretion disk and jets, which were clearly seen in the X-ray images recently captured by the Chandra Observatory. It is also hard to explain why some pulsars are gamma rays only [16,17].

Recently, the author has developed a new mechanism for supernova explosion caused by gravitational field shielding [18], in accordance with his five-dimensional (5D) fully covariant Kaluza-Klein theory with a scalar field [8,19,20]. According to the gravitational field shielding theory, a supernova explosion takes place when its core collapses to a critical density where the gravitational field suddenly disappears or is shielded by the strong scalar field. At this moment, the extremely large pressure of matter immediately stops the core from collapsing and then the core quickly expands to powerfully push the mantle part of the supernova moving radially outward as a supernova explosion. As the core expands, the gravity resumes. After the mantle explodes out of the supernova, the core is left as a neutron star and starts to oscillate about its equilibrium of gravity and pressure. Rather than the rotation, acoustic wave and neutrino driven mechanisms of supernova explosions, this new mechanism is driven by the extreme pressure of the core when the gravitational field is suddenly weakened by the strong scalar field.

In this paper, we develop a physical model of pulsars, through which we propose an alternative explanation for neutron stars to emit the Dirac-delta-shape pulse-like radio frequency radiation and the Lorentzian shape oscillating X-rays, in terms of the 5D gravitational field shielding theory and the self-gravitating oscillations of neutron stars. We will also discuss how the frequency of emissions depends on the mass of the neutron star, the initial conditions, the equation of state, and the frozen magnetic field. In contrast to the conceptual lighthouse model, this physical oscillating model is based on the simple physics of thermal and accelerating charged particle radiation and the 5D gravity, and predicts power-time profiles of pulsars that are highly consistent with the measurements and observations.

2 Emissions of oscillating neutron stars

As described above, a neutron star starts to oscillate about its equilibrium of gravity and pressure once the mantle is exploded out of the supernova. The oscillation of the neutron star oscillates or accelerates inside particles. At the surface or in the crust, the acceleration of particles can be simply given by the following equation of motion,

$$a(t) \equiv \frac{d^2R(t)}{dt^2} = -g(R) - \frac{1}{\rho(R)}\frac{dP(\rho)}{dR}, \tag{1}$$

where $a(t)$ is the acceleration of the particle; $R(t)$ is the radial distance of the particle or simply the radius of the neutron star; $\rho(R)$ is the density of neutron star; $P(\rho)$ is the pressure of neutron star, which in this study is given by the Skyrme model for the Equation of State (EOS) of neutron stars [21,22],

$$P = 5.32\times10^9\rho^{5/3} + 1.632\times10^{-5}\rho^{8/3} - 1.381\times10^5\rho^2, \tag{2}$$

in the cgs unit system; and $g(R)$ is the gravitational field or acceleration, which in this study is determined according to the five-dimensional fully covariant Kaluza-Klein gravitational shielding theory with a scalar field that the author previously developed [18],

$$g = \frac{c^2}{2\phi^2}\left(\frac{d\phi}{dr} + \phi\frac{d\nu}{dr}\right)e^{-\lambda}, \tag{3}$$

in the Einstein frame. Here the scalar field ϕ, the metric 00- and 11-components e^ν and e^λ were solved as ([19] and references therein)

$$\phi^2 = -\alpha^2\psi^4 + (1+\alpha^2)\psi^{-2}, \tag{4}$$

$$e^\nu = \psi^2\phi^{-2}, \tag{5}$$

$$e^\lambda = \left(1 - \frac{B^2}{r^2}\right)^2\psi^{-2}, \tag{6}$$

in the Jordan frame, where ψ, B, and α are given by

$$\psi = \left(\frac{r-B}{r+B}\right)^{1/\sqrt{3}}, \tag{7}$$

$$B = \frac{GM}{\sqrt{3(1+\alpha^2)}\,c^2}, \tag{8}$$

$$\alpha = \frac{Q}{2\sqrt{G}M}. \tag{9}$$

This solution does not have an unknown parameter and reduces to the Schwarzschild solution in the Einstein frame when fields are weak and matter that generates the fields is neutral [8,18,23]. The weak field tests of general relativity are also the tests of this 5D gravity. In the case of strong fields, especially charged, the 5D gravity gives new effects such as the space polarization [24,25], electric redshift [19], gravitational field shielding or spacetime flattening [18], gravitationless black hole [23], and so on. The new effects are results of the strong scalar field, which significantly reduces the local gravity or, in other words, decreases the equivalent gravitational constant [20].

Figure 4a plots the radial distance as a function of time that is obtained from numerically solving (1). The result indicates that the neutron star nonlinear periodically oscillates, non-uniformly with quick stop and bounce by the pressure force when the gravity loses its dominance. It is in a dynamic equilibrium state rather than a static one. According to the gravitational shielding model [18], a supernova explosion takes place, due to the extremely large pressure pushing outward, when its core collapses to a critical density, at which the gravitational field suddenly disappears or is shed by the strong scalar field. Once a supernova or a dying star has exploded its mantle, the core as a stellar remnant forms a neutron star, located at the center of the supernova progenitor, with a relative large initial radius where the gravity is resumed. Then, the formed neutron star starts to gravitationally compress from its initial state. As it squeezes, the scalar field increases and reduces the gravitational field or flattens the spacetime again. To about the critical density, the gravitational field is disappeared or shed again by the strong scalar field. At this moment, the extensive pressure immediately stops the neutron star from the further collapse and extremely drives the neutron star to rapidly expand. Particles are extremely accelerated by the extensive pressure when the gravitational field is shed. After the neutron star is sufficiently expanded, the gravity resumes because the scalar field is weakened. When the gravity becomes dominant, the neutron star collapses again. This periodic switching of the dominance between the gravity and the pressure force leads to a nonlinear oscillation of the neutron star. Here in Figure 4 as an example we have chosen the mass of the neutron star to be about 1.5

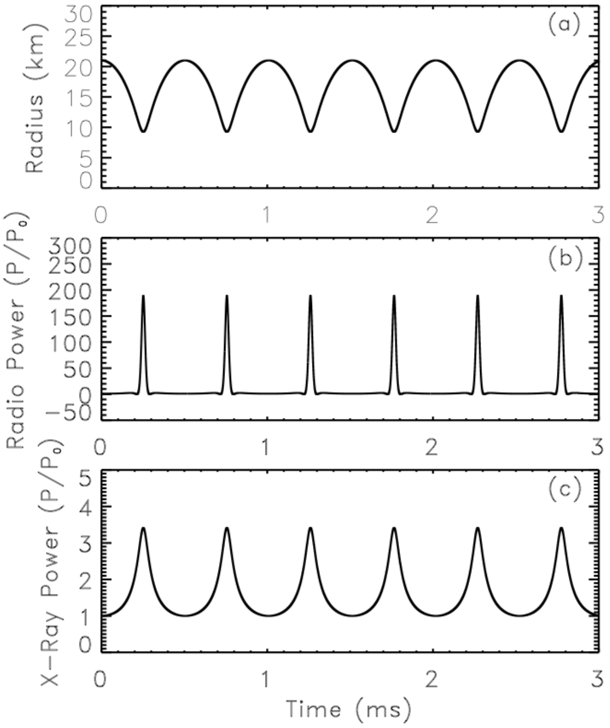

Fig. 4: Oscillation of a neutron star with 1.5 solar masses versus synchronous emissions of the Dirac Delta shape radio pulses and the Lorentzian shape X-ray oscillations. The radial distance (a), the power of radio emission (b), and the power of X-ray emission (c) are plotted as functions of time. The initial conditions for the radial distance and velocity of oscillation are chosen to be $R_0 = 22$ km and $\upsilon_0 = 0$.

solar masses; and the initial radial distance and velocity to be about $R_0 = 22$ km and $\upsilon_0 = 0$, respectively.

The accelerating particles, if electrically charged, generate radio emissions. According to the Larmor equation [26], the power of radio emissions generated by the accelerating charged particle is proportional to the square of the magnitude of the acceleration,

$$P_r(t) = \frac{q^2 a^2(t)}{6\pi\epsilon_0 c^3} \propto a^2(t), \tag{10}$$

where q is the particle charge; ϵ_0 is the dielectric constant in the free space; and c is the speed of light in free space. Figure 4b plots the power of radio emissions normalized to the power at the initial state, in terms of the Larmor equation (10) and the acceleration (1). The result indicates that the radio emissions by the nonlinearly oscillating neutron star are periodically pulse-like radiation with the Dirac delta shape, which is consistent with the general observations of pulsars. A neutron star could be possibly charged as a consequence of holding some certain amount of net protons or nuclei. The fraction and effect of protons in neutron stars have been considered for years [27,28]. To explain the observations of Geminga, a model of a dense neutron star with localized protons was proposed [29,30]. In [28], the maximum amount of charge in a compact star can be $\sim \sqrt{G}M$, which is $\sim 2.5 \times 10^{20}$ C for a neutron star with 1.5 solar masses.

On the other hand, a hot neutron star can emit thermal or blackbody radiation in the frequency range of X-rays. For instance, according to Wien's law, the frequency of blackbody radiation at the maximum or at the peak of the power by a hot body with surface temperature of 100 million Kelvins is about 10^{19} Hz, which is in the frequency range of X-rays. The total power of X-rays emitted by a hot neutron star can be given by

$$P_X(t) = 4\pi R^2(t)\,\sigma T^4(t) \propto R^{-\delta}(t), \tag{11}$$

where σ is the Stefan-Boltzmann constant. Here we have also considered that the surface temperature of the neutron star varies as the neutron star oscillates, or in other words, the temperature is a function of the radius or density. Figure 4c plots the power of X-rays normalized to the initial power, in terms of the blackbody radiation or (11). Here we have chosen the index $\delta = 3/2$, which corresponds to $T \propto R^{-(\delta+2)/4} = R^{-7/8}$. Choosing a larger δ does not alter the shape of the radiation, but can lead to a more significant oscillation of X-ray emissions, because the variation of temperature responding to the oscillation of neutron star increases with the index δ. The result shown in Figure 1c indicates that the X-rays emitted by the nonlinearly oscillating neutron star are synchronous periodically oscillating blackbody radiation with the Lorentzian shape, which is also consistent with the general observations of pulsars.

A neutron star may have a temperature as high as thousand billion degrees (10^{12} K) at the moment of its birth by an explosion of a supernova and then quickly cools down to a hundred million degrees (10^8 K) because of its strong radiation and neutrino emissions [31]. Therefore, for an early-aged neutron star, if the temperature is above 10^{10} K, the dominant thermal or blackbody radiation can be gamma rays. In other words, a younger pulsar as a hotter neutron star can emit gamma-rays mainly, which may explain the gamma ray only pulsars recently measured by NASA's Fermi Gamma Ray Telescope [32,33].

The frequency of the pulses shown in Figure 4 is about 2000 Hz (with a period of about 0.5 milliseconds), which depends on (1) the mass of the neutron star, (2) the initial kinetic and potential energy of the neutron star (or initial conditions of R_0 and υ_0), and (3) the applied EOS. In general, at the same initial conditions with the same applied EOS, the pulse frequency is higher if the mass of the neutron star is greater because a larger mass, and thus larger gravity, collapses the neutron star quicker. Figures 5 and 6 show, respectively, the radial distance and the radio emission power for oscillating neutron stars with four different masses under the same initial conditions and the same applied EOS. It is seen that the frequency decreases with decreasing neutron star mass. For a

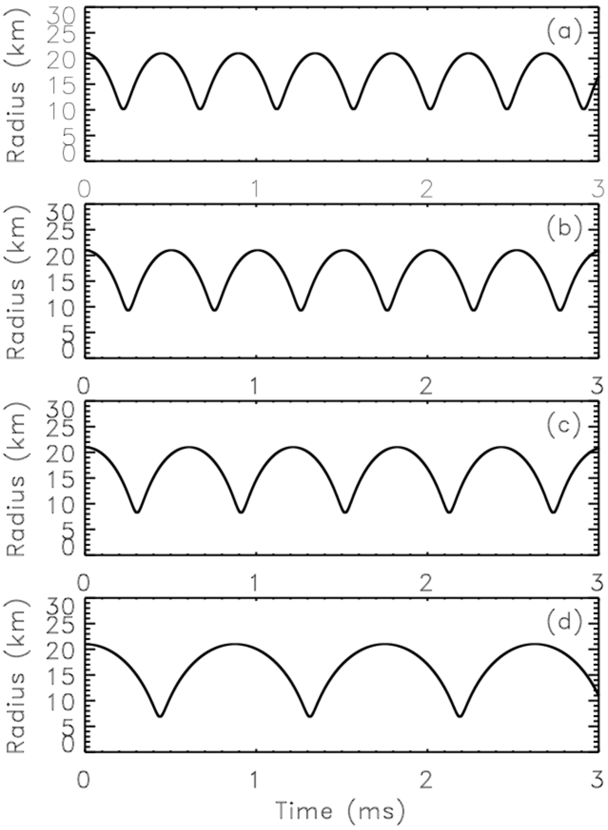

Fig. 5: Oscillations of neutron stars. The radial distance is plotted as a function of time for neutron stars with mass equal to 2, 1.5, 1, and 0.5 solar masses, respectively, from (a) through (d). The initial conditions and applied EOS are the same as in Figure 4.

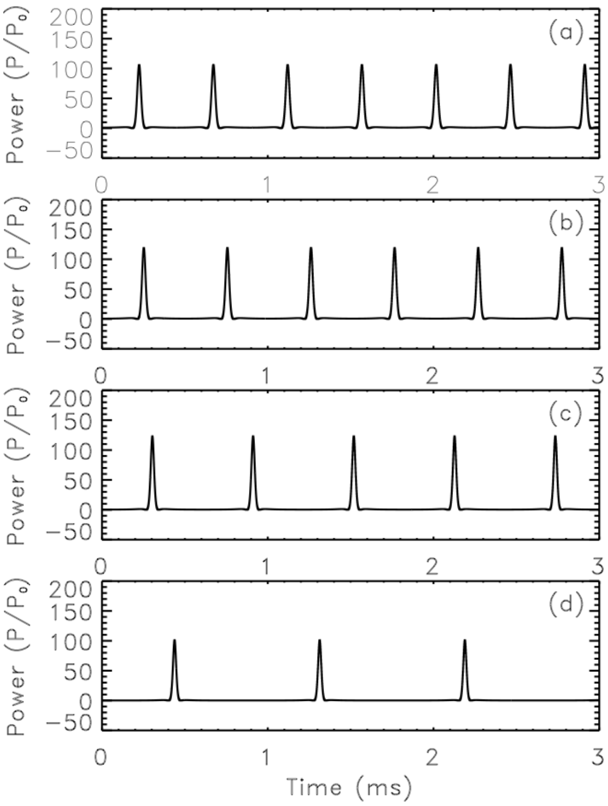

Fig. 6: Radio emissions of oscillating neutron stars. The power of radio emissions for neutron stars with mass equal to 2, 1.5, 1, and 0.5 solar masses, respectively, from (a) through (d). The initial conditions and applied EOS are the same as in Figure 5. The powers for all cases are normalized.

neutron star with mass four times smaller, the pulse frequency will be twice lower. The oscillation model of pulsars also gives very precise intervals between pulses as shown in Figures 3 to 5. Different pulsars can have quite different periods of pulses because they have different masses and start their oscillations from different initial states. Given a neutron star, the periodic switch between gravity and pressure dominant forces does not vary the period or frequency of oscillation.

3 Discussions and conclusions

For neutron stars with the same mass and the same applied EOS, the frequency of pulses is lower if the initial R_0 or v_0 is greater, because it takes a longer time to make one oscillation not only due to the longer course for the oscillation but also due to the weaker initial gravity. For neutron stars with the same mass and at the same initial state of motion, the frequency is greater if the density dependence of the pressure determined by the EOS is harder, because the pressure gradient push is greater and thus the oscillation is faster. On the other hand, the oscillation of the neutron star compresses and relaxes the frozen magnetic field of the neutron star as well as varies the particle radial speed of motion. The magnetic pressure and speed gradients also play some role in resisting the oscillations and thus decreasing the frequency of the oscillations, but not changing the emission characteristics. Therefore, oscillation periods of neutron stars can be in a wide range [34,35], when all these effects are considered. Details on these effects will be studied next.

The oscillation of a neutron star will be damped and thus slowed down due to the loss of energy or mass. Neutron stars can speed up their oscillations when they accrete more energy or mass than they lose. They may also twitch or glitch their pulses when their states of matter suddenly change [36,37]. Very hot neutron stars (e.g. 10^{10} K) may emit oscillating gamma rays [38,39]. Sufficiently cooled down neutron stars (e.g. 10^6 K) can emit oscillating ultraviolet radiation [40]. All the temperature-related emissions are periodically oscillating with the Lorentzian shape. Only the acceleration-related radio frequency emissions are pulse-like with the Dirac delta shape. Since electrons have much smaller inertia than nuclei, the pressure gradient buoyant forces accelerate them in different strengths with time lag. Therefore, the radio emissions from electrons and nuclei in the neutral crust of an oscillating neutron star are not completely destructed. Net radio emissions from the electrons and nuclei in the neutral crust of a neutron star can be generated by the self-gravitating oscillating neutron star. Due to the time lag, each primary pulse, which is produced by electrons, may follow a secondary pulse, which is produced by nuclei.

The sudden disappearance of gravitational field due to the shielding by the strong scalar field is significant for the radio emissions of neutron stars to be pulses with the Dirac delta shape. Under the Newtonian and Einsteinian gravitational theories, the gravitational oscillations of neutron stars may also produce the observed Dirac delta shape radio emissions, but need the neutron star to be over compressed in order for the pressure gradient push to dominate the non-shielding strong gravity. On the other hand, it should be noted that (1) and (2) are valid only for non-relativistic motion. According to the calculation done in Figure 1, we can see that the maximum speed of the oscillation is less than about one third of the light speed in vacuum. In this case, we have a relativistic factor $\gamma < 1.1$, which means that the relativistic effect is not significant and thus negligible. The shape of radio emissions depends on the acceleration of charged particles and the shape of X-ray emissions depends on the surface temperature or radius of the neutron star. This physical model quantitatively explains the emission characteristics of pulsars.

The energy dissipation deficiently decreases the neutron star's total energy, mass, amplitude of oscillation, EOS (or the bounce of the neutron star), magnetic field strength, and thus slightly changes or reduces both the power and frequency of pulses. The small energy dissipation or loss due to radiation (or damping) can only weakly slow down the pulses. The measured polarizations of pulsars can be considered as the causes of particles flowing, electromagnetic activities, and unevenly distributed surface temperatures. This paper has only addressed the radio emission of charged particles that are accelerated due to the oscillation of the neutron star. If we also consider the radio emission of charged particles that are accelerated due to particle flowing and electromagnetic activities, the pulse profiles should be polarized with multiple components [41–43] and complicated pulse profiles. The Dirac-delta shape and Lorentzian shape are only the main characteristics (i.e. periodicities) of radio pulses and X-ray emissions. The emissions of pulsars are gravitation-powered with effects of rotation, accretion, and/or magnetism, respectively. The gravitational (or oscillatory) energy dissipation provides the power for the pulsar-nebula system. The radio emissions are coherent with high brightness temperature because charged particles are coherently accelerated along with the oscillation of neutron stars. The X-ray emission of a pulsar is thermal but with the temperature varying in a range rather than a single temperature. To obtain the energy spectra of X-rays, we must integrate the flux of emission over a temperature range. The result of integration should be nonthermal as measured. All these aspects will be explored in details in future.

As a summary, we have developed a physical model of pulsars to quantitatively interpret the emission characteristics of pulsars, in accordance with the five-dimensional fully covariant Kaluza-Klein gravitational shielding theory and the physics of thermal and accelerating charged particle radiation. With the significant gravitational shielding by the strong scalar field, a neutron star nonlinearly oscillates and produces synchronous periodically Dirac-delta-shape pulse-like radio-frequency radiation as well as periodically Lorentzian shape oscillating X-rays. The oscillating or accelerating charged particles produce the Dirac-delta-shape pulse-like radio frequency radiation, while the thermal/blackbody radiation of neutron stars that oscillate and thus vary the temperature produces the Lorentzian shape X-rays. This physical model of pulsars as gravitational shielding and oscillating neutron stars broadens our understanding of neutron stars and develops an innovative mechanism to disclose the mystery of pulsars.

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