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An Explanation for the Undetection of Radio Pulsar in Supernova 1987A *

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Supernova 1987A is a core collapse supernova in the Large Magellanic Cloud, inside which the product is most likely a neutron star. Despite the most sensitive available detection instruments from radio to γ-ray wavebands being exploited in the pass thirty years, there have not yet been any pulse signals detected. By considering the density of the medium plasma in the remnant of 1987A, we find that the plasma cut-off frequency is approximately 7 GHz, a value higher than the conventional observational waveband of radio pulsars. As derived, with the expansion of the supernova remnant, the radio signal will be detected in 2073 A.D. at 3 GHz.

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Neutron star (NS) is believed to form during the core collapse supernova (SN) explosion of the massive star, which may be related to the supernova remnant (SNR).[1] However, pulsar is thought of as the fast rotating and highly magnetized NS, whose radio emission is produced by a pair plasma accelerating in the strong electric and magnetic field in the polar gap of NS.[2–4] So far, there have been ~ 400 SNRs detected in the Milky Way, where only approximately one quarter are verified to be associated with the pulsars.[5] It is still an open question about why there are no pulsars detected in so many SNRs.

SN 1987A, which was detected in the Large Magellanic Cloud in 1987,[6] is a core collapse supernova of a blue supergiant star with the mass of $\sim$16–22 $M_{\odot}$.[7] From the observation of the initial neutrino burst of SN 1987A, Arnett *et al.*[8] suggested that a compact object may be formed during this core collapse, which is most likely an NS.[7] However, Gaensler *et al.*[9] argued that the flat radio spectrum of SN 1987A may be associated with a pulsar wind nebula (PWN) or an accreting black hole. Recently, based on the combination analysis of morphological and spectral data of SN 1987A with the Australian telescope compact array and the Atacama large millimeter/submillimeter array,[10–12] Zanardo *et al.*[11] suggested that there may be a PWN powered by a pulsar present inside SNR. Although great efforts have been taken to search for the pulsar inside the SN 1987A, there is no definite radio pulse signal reported,[10,11,13] which can only give the estimated upper limit of the pulsar luminosity of a few tens of the solar luminosity.

In this Letter, we hypothesize that there is a crab-like NS inside the SN 1987A, which can accrete the matter of the SNR to its polar gap along the magnetic field, and exert influence on the radio emission. We propose an explanation for the failed detection of the radio pulse of the NS by considering the effects of the plasma cut-off oscillation frequency.

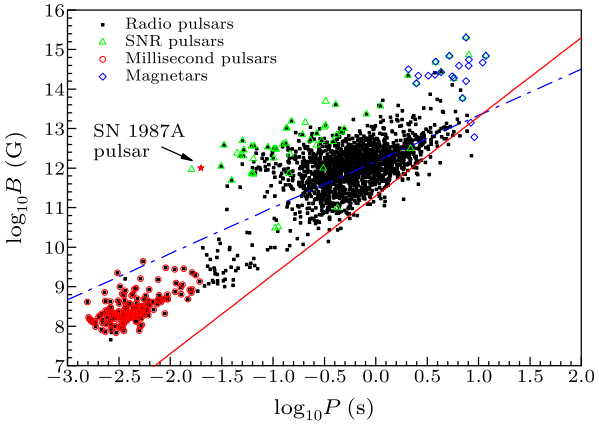

Fig. 1. Period versus magnetic field diagram of various pulsars. Dots are radio pulsars, triangles are SNR pulsars, circles are millisecond pulsars, and diamonds are magnetars. The dashed-dotted and solid lines are spin-up and death lines, respectively.

It is believed that a pulsar with a high kick speed of $\sim 400 \pm 40$ km/s may be formed after the core collapse supernova of a massive star.[2] As the pulsar moves, the surrounding matters in the SNR can be captured by the pulsar through the gravitational and electromagnetic force, and channeled along the magnetic field into the polar caps. If the particle density in the polar caps is high enough, the plasma oscillation frequency may reach or pass the radio radiation frequency, resulting in that the radio signal from the pulsar cannot

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be detected. We suggest that there may be a crab-like pulsar formed in SN 1987A with the period of $P_{\rm i} \sim 20\,{\rm ms}$ and magnetic field of $B_{\rm i} \sim 5 \times 10^{12}\,{\rm G}$ (see its period-magnetic field position in Fig. 1). The radio emission beam of the pulsar should sweep across the earth, while this radio signal cannot be detected due to the high particle density in the pulsar gaps, which cut off the propagation of the pulsar radio waves. We predict that with the further expansion of the SNR and the spin down of the pulsar, its radio pulse signal will be detected someday.

The propagation of the electromagnetic wave in the charged medium will be influenced by the plasma oscillation frequency ν (or the plasma cut frequency),[14]

$$\nu = \sqrt{\frac{ne^2}{\pi m_{\rm e}}} = 8980\Big(\frac{n}{1\,{\rm cm}^{-3}}\Big)^{\frac{1}{2}}\,({\rm Hz}), \tag{1}$$

where e and $m_{\rm e}$ are the charge and mass of the electron, respectively, and n is the electron number density of the plasma and can be inferred as follows:

$$n = \frac{\dot{M}}{2S_{\rm H}v_{\rm H}m_{\rm p}}, \tag{2}$$

with $\dot{M}$ being the accretion rate, $m_{\rm p}$ being the proton mass, $S_{\rm H}$ and $v_{\rm H}$ being the cross sectional area and the fall velocity of the accretion matters at the height H of the polar gap, respectively. These parameters can be determined as follows: for $\dot{M}$, as the pulsar moves in the remnant, the accretion rate can be written as[15]

$$\dot{M} = \frac{4\pi\rho_{\rm p}G^2M^2}{v_{\rm p}^3}, \tag{3}$$

where G is the gravitational constant, M is the NS mass, $v_{\rm p}$ is the proper motion velocity of the pulsar, and $\rho_{\rm p}$ is the average plasma density in the remnant,

$$\rho_{\rm p} = \frac{M_{\rm p}}{V}, \tag{4}$$

with $V \sim 4\pi l_{\rm R}^3/3$ being the volume of SN 1987A, $l_{\rm R} \sim 0.6\,{\rm l.y.}$ (light-year) is the scale of the remnant,[16] and $M_{\rm p} \sim 20\,M_\odot$ being the mass of the progenitor.

For $S_{\rm H}$ and $v_{\rm H}$, firstly we introduce the height of the polar gap: most models on pulsar radio radiation argue that the height h of radio emission satisfies $h < 0.1R_{\rm l}$,[17] where $R_{\rm l} = Pc/2\pi$ is the light cylinder radius of the pulsar, with P and c being the period of pulsar and the speed of light, respectively.[18]

Thus the maximum height H is

$$H = 0.1R_{\rm l} = \frac{Pc}{20\pi}. \tag{5}$$

Secondly, for the dipole magnetic field, the last closed magnetic field line can be obtained by $r = R_{\rm l}\sin^2\theta$, where θ is the angle between the radial vector of the magnetic field line and the spin axis.[19] Thus the corresponding equation at the height H is

$$\frac{H}{\cos\theta_{\rm H}} = R_{\rm l}\sin^2\theta_{\rm H}, \tag{6}$$

where $\theta_{\rm H}$ is the angle between the radial vector of the magnetic field line at the height H.

Finally, the area of the polar gap can be obtained,

$$S_{\rm H} = 2\pi H^2(1-\cos\theta_{\rm H}), \tag{7}$$

and the falling velocity of the accretion matters is

$$v_{\rm H} = \sqrt{\frac{2GM}{H}}. \tag{8}$$

Substituting Eqs. (3), (4), (7) and (8) into Eqs. (1) and (2), we can obtain the proton number density and plasma oscillation frequency at the emission origin,

$$n = \frac{300\sqrt{10\pi}G^{3/2}M^{3/2}M_{\rm p}}{m_{\rm p}c^{3/2}v_{\rm p}^3P_{\rm i}^{3/2}l_{\rm R}^3}, \tag{9}$$

$$\nu = 8980\sqrt{n}\,({\rm Hz}). \tag{10}$$

Assuming $M \sim 1.4\,M_\odot$, $v_{\rm p} = 400\,{\rm km/s}$ and $P_{\rm i} = 20\,{\rm ms}$, substituting the observed $l_{\rm R} \sim 0.6\,{\rm l.y.}$[16] into Eqs. (9) and (10), we can obtain $\nu \sim 7\,{\rm GHz}$, which is over the observation waveband of the radio telescope.

With the expansion of the SNR and the evolution of the pulsar, the radio pulse of the pulsar may be detected in low frequency (1.4 GHz, for example), which is suitable for most radio telescopes. Next, we consider the evolution of the plasma oscillation frequency.

The evolution of the spin period for the pulsar in SN 1987A is

$$P_{\rm t} = \sqrt{2(t-t_{\rm i})(P_{\rm i}\dot{P}_{\rm i}) + P_{\rm i}^2}, \tag{11}$$

where $t_{\rm i} = 9.46 \times 10^8\,{\rm s}$ is the present age of the pulsar in SN 1987A.

For the remanent, the maximum line of sight velocity of the ejecta in the ring plane is[20]

$$v_{\rm t} = 3.57 \times 10^{17}\Big(\frac{t}{1\,{\rm s}}\Big)^{-1}\,({\rm cm/s}). \tag{12}$$

The equation expansion of the remnant radius is

$$R_{\rm t} = l_{\rm R} + \int_{t_{\rm i}}^{t} v_{\rm t}dt. \tag{13}$$

Integrating Eqs. (9)–(13), the evolution equation of the proton number density and the plasma oscillation frequency are obtained as

$$n_{\rm t} = \frac{300\sqrt{10\pi}{\rm G}^{\frac{3}{2}}M^{\frac{3}{2}}M_{\rm p}}{m_{\rm p}c^{\frac{3}{2}}v_{\rm p}^3}P_{\rm t}^{-\frac{3}{2}}R_{\rm t}^{-3}, \tag{14}$$

$$\nu_{\rm t} = 8980\sqrt{n_{\rm t}} \propto P_{\rm t}^{-\frac{3}{4}}R_{\rm t}^{-\frac{3}{2}}. \tag{15}$$

We obtain that if $\nu_{\rm t} = 5\,{\rm GHz}$, $t \sim 43\,{\rm yr}$; $\nu_{\rm t} = 3\,{\rm GHz}$, $t \sim 86\,{\rm yr}$; $\nu_{\rm t} = 1.4\,{\rm GHz}$, $t \sim 300\,{\rm yr}$. More details are shown in Fig. 2.

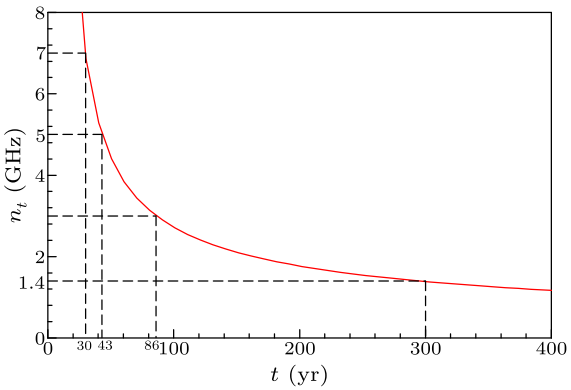

Fig. 2. The evolution curve of the plasma oscillation frequency.

SN 1987A serves a unique opportunity to bridge the gap between the progenitor star and its evolutional products. Recently observations by Zanardo *et al.*[11] and Indebetouw *et al.*[10] for the SN 1987A suggested that a PWN may be present at the west of the SN site, and would imply a possible pulsar which has a natal kick of $\sim 400\,{\rm km/s}$. However, there has not been any pulse signal detected up to now, which has confused researchers for many years. It is possible that the radio emission beam of the pulsar in SN 1987A does not sweep across the earth or the pulsar does not have radio emission. We think that the pulse signal cannot be detected at present, even if the radio emission beam sweeps across the earth. Considering the density of the medium plasma in the remnant of 1987A, which will block the propagation of the radio waves of pulsar, we find that (1) the plasma oscillation frequency is about 7 GHz, which is over the observational wavebands of most radio pulsars; (2) with the expansion of the SNR and the spin down of the pulsar, the radio pulse of the pulsar in SN 1987A may be detected at 5 GHz in 2030 A.D., at 3 GHz in 2073 A.D., approximately; (3) as an estimation of the crab-like pulsar after the SN explosion, it needs about 300 y to be detected at 1.4 GHz radio waveband, while the plasma density of SNR decreases.

For the pulsar in SN 1987A, we assume that the predecessor mass $M_{\rm p} = 20\,M_{\odot}$, the proper motion $v_{\rm p} = 400\,{\rm km/s}$, the spin period $P_{\rm i} = 20\,{\rm ms}$ and the plasma in SN 1987A are distributed evenly. Actually, we cannot guarantee these. The plasma oscillation frequencies at present under the condition of different parameters may be different.

Generally, for the radio spectrum of pulsar, the flux density S_ν changes with frequency according to the power low $S_\nu \propto \nu^{-\alpha}$, with α in the range of 2–4.[2,3] Thus it is more difficult to detect pulsars in high-frequency radio band than that in low-frequency radio band. In addition, the high-energy emission (such as x-ray and γ-ray) from the pulsar in SN 1987A can propagate through the plasma. However, there is no high-energy pulse from SN 1987A that has been detected. It is possible that the high-energy emission from the pulsar is weaker than that from the remnant.

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