

# Implications of the Discovery of a Millisecond Pulsar in SN 1987A

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From the observation of a millisecond pulsar in SN 1987A, the following implications are obtained. 1) The pulsar spindown in SN 1987A is caused by radiating gravitational waves rather than by magnetic dipole radiation and/or relativistic pulsar winds. 2) A mildly deformed shock wave would be formed at the core-collapse and explosion in SN 1987A, which is consistent with the conclusion given in Nagataki (2000). 3) The gravitational waves from the pulsar should be detected in several years using a Fabry-Perot-Michelson interferometer as the gravitational detector, such as LIGO and TAMA. 4) The neutrino oscillation model is not a promising model for the explanation of the kick velocity of the pulsar in SN 1987A. The hydrodynamical instability model is more favored.

## §1. Introduction

Since there is little information concerning the pulsar in the remnant of SN 1987A, its properties, such as angular velocity of rotation, strength of magnetic fields, and total baryon mass, have been treated as free parameters or output parameters.<sup>1)–4)</sup> However, Middleditch et al. (2000) reported the discovery of an optical pulsar whose frequency is 467.5 Hz and spindown rate is  $(2-3)\times 10^{-10}$  Hz s<sup>-1</sup>.<sup>5)</sup> Since some free parameters appearing in previous papers are constrained by this discovery, we consider its implications in this paper. In section 2, we show that the spindown is caused by radiating gravitational waves rather than by magnetic dipole radiation and/or relativistic pulsar winds. We also determine constraints on the strength of the magnetic field of the pulsar. In section 3, we discuss the effects of the proto-neutron star's angular momentum on the dynamics of the core collapse of the progenitor of SN 1987A. The amplitude of the gravitational waves from the pulsar and its detectability are discussed in section 4. Implications of the kick velocity of the newly-born pulsar are presented in section 5.

## §2. Origin of the pulsar spindown

Middleditch et al. (2000) reported that the spindowns  $(2-3)\times 10^{-10}$  Hz s<sup>-1</sup> of the 2.14 ms pulsations should be caused by radiating gravitational waves. This is because the relation between the spindown rate and its modulation period can be explained at the same time by adding the non-axisymmetric component of the

moment of inertia ( $\delta I$ ) to a spherical neutron star whose moment of inertia is  $I$ . It is true that this conclusion is curious, because the spindown of a normal pulsar is believed to be caused by magnetic dipole radiation<sup>6)</sup> and/or relativistic pulsar winds.<sup>7)</sup> However, we want to emphasize that their conclusion is supported by the recent UVOIR bolometric light curve. We can easily calculate the decreasing rate of the rotational kinetic energy of the pulsar as

$$\frac{dE}{dt} \equiv \dot{E} = I\Omega \frac{d\Omega}{dt}, \quad (2.1)$$

where  $\Omega$  is the angular velocity of the pulsar. Assuming that the pulsar is spherical and has a constant density, the moment of inertia of the pulsar can be expressed as

$$I = 1.1 \times 10^{45} \left( \frac{M}{1.4 M_{\odot}} \right) \left( \frac{R}{10 \text{ km}} \right)^2 \text{ [g cm}^2\text{]}. \quad (2.2)$$

Thus, using the observation of  $\Omega$  and  $\dot{\Omega}$ , we can estimate  $\dot{E}$  as

$$\dot{E} = -(4 - 6) \times 10^{39} \left( \frac{M}{1.4 M_{\odot}} \right) \left( \frac{R}{10 \text{ km}} \right)^2 \text{ [erg s}^{-1}\text{]}, \quad (2.3)$$

which is much larger than the UVOIR bolometric luminosity,  $(1-2) \times 10^{36} \text{ erg s}^{-1}$ .<sup>8)</sup> This discussion strongly supports that the pulsar spindown is caused by radiating gravitational waves. Otherwise, the supernova remnant would become much brighter.

We must also check whether the remnant is bright in other wavelengths, such as radio, X-ray, and gamma-ray. If the brightness of the remnant in these frequencies is not too large, we can confirm more strongly our hypothesis that the pulsar spindown is caused by radiating gravitational waves.

It is reported that the radio emission spectrum is well fitted as<sup>9)</sup>

$$S \sim 10^{-15} \left( \frac{\nu}{1 \text{ GHz}} \right)^{-1} \text{ [erg s}^{-1} \text{ cm}^{-2} \text{ GHz}^{-1}\text{]}. \quad (2.4)$$

In obtaining this expression, Gaensler et al.<sup>9)</sup> used data at frequencies of 1.4, 2.4, 4.8, and 8.6 GHz. Therefore, when we assume that this power-law fitting holds at all radio frequencies, we can estimate its luminosity as

$$L_{\text{radio}} \sim 3 \times 10^{32} \left( \frac{D}{50 \text{ kpc}} \right)^2 \log_e \left( \frac{\nu_{\text{max}}}{\nu_{\text{min}}} \right), \quad (2.5)$$

where  $D$  and  $\nu$  are the distance from the Earth to the remnant and the radio frequency, respectively. Assuming that the distance is 50 kpc,<sup>10)</sup> we find that the luminosity in the radio band is much smaller than the rate at which the rotational energy decreases. In fact, unless  $\nu_{\text{min}}$  is as small as  $10^{-10^6} \text{ Hz}$ , the luminosity in the radio band is not comparable to the rate at which the rotational energy decreases. Moreover, it is generally believed that the radio emission does not come from the pulsar but from the synchrotron emission of electrons that is generated when the shock encounters circumstellar matter.<sup>9)</sup>

An upper limit for X-rays of  $2.3 \times 10^{34}$  erg s<sup>-1</sup> (0.5 – 2 keV) has been placed by the *Chandra* observations of the remnant.<sup>11)</sup> They also discussed that this low upper limit is not surprising in view of calculations showing that debris should still be opaque to soft X-rays.<sup>12)</sup> Hence we can conclude that the rapid rate at which the rotational energy decreases cannot be explained by the emission of the soft X-rays.

The remnant is thought to be transparent to hard X-rays and gamma-rays. In fact, Fransson and Chevalier<sup>12)</sup> reported that the energy corresponding to unity of the absorption optical depth of the ejecta can be well represented by the formula

$$E(\tau = 1) = 81 \left( \frac{M_c}{1 M_\odot} \right)^{0.36} \left( \frac{V_c}{2500 \text{ km s}^{-1}} \right)^{-0.72} \left( \frac{t}{1 \text{ yr}} \right)^{-0.72} \quad [\text{keV}], \quad (2.6)$$

where  $M_c$ ,  $V_c$ , and  $t$  are the mass inside the O/He interface, the expansion velocity of the core, and the time from the explosion, respectively. When we adopt  $M_c = 3.7 M_\odot$ ,<sup>3)</sup>  $V_c = 2500 \text{ km s}^{-1}$ ,<sup>4)</sup> and  $t = 5 \text{ yr}$ , we obtain  $E(\tau = 1) = 40 \text{ keV}$ . Thus the situation here is different from that for soft X-rays; that is, the remnant is thought to be transparent to hard X-rays and gamma-rays. As for the data at these frequencies, the upper limit of the spectrum is rather rough, and published data are not new. The gamma-ray continuum from April 4, 1989 can be fit as<sup>13)</sup>

$$\frac{dN}{dE} = 1.6 \times 10^{-5} \left( \frac{E}{100 \text{ keV}} \right)^{-1} \quad [\text{photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}] \quad (2.7)$$

for the energy range 50-800 keV. The total energy flux can be obtained as

$$L_{\text{gamma}} \sim 8 \times 10^{37} \left( \frac{D}{50 \text{ kpc}} \right)^2 \left( \frac{E_{\text{max}}}{100 \text{ keV}} \right), \quad (2.8)$$

where  $E_{\text{max}}$  is the maximum energy of the gamma-ray photons. It is generally believed that these gamma-rays come from radioactive nuclei such as <sup>56</sup>Co and <sup>57</sup>Co.<sup>14)</sup> Moreover, the Crab nebula, whose energy source is the central pulsar, is brightest in the X-ray band. Thus it is difficult to think that the remnant in SN 1987A could be brightest in the gamma-ray band and its luminosity could be comparable to the rate at which the rotational energy decreases. In the case that the total gamma-ray luminosity is found by future observations to be as large as the rate at which the rotational energy decreases, we will have to consider the serious problem of producing gamma-rays only. That is, we have to face the difficult problem of determining a mechanism that produces only gamma-rays and no photons in other energy bands from the pulsar.

For the reasons mentioned above, we think that it is difficult to explain the observed spindown with the magnetic dipole model and/or relativistic pulsar wind model. However, it is necessary to fix a strict upper limit of the present gamma-ray flux from SN 1987A in order to conclude with certainty that the pulsar spindown is not caused by radiating photons and/or ejecting relativistic particles but by gravitational waves.

We can also give an upper limit for the strength of the magnetic field of the pulsar. From the magnetic dipole model and/or the relativistic pulsar wind model,

the rate at which the energy decreases can be written<sup>7)</sup>

$$\dot{E} = -\frac{B_p^2 R^6 \Omega^4}{c^3}, \quad (2.9)$$

where  $B_p$  is the strength of the magnetic field at the magnetic pole of the star. From Eqs. (2.3) and (2.9), we can derive the upper limit for  $B_p$  as

$$B_p \leq (4 - 5) \times 10^{10} \left( \frac{M}{1.4 M_\odot} \right) \left( \frac{10 \text{ km}}{R} \right)^4 \text{ [G]}. \quad (2.10)$$

Since the strength of the magnetic field is so weak, we believe that a neutron star without hot spots will be found in X-ray bands in the near future. The lack of hot spots implies that the surface temperature of such a neutron star will be approximately uniform. Such a neutron star should be found when the optical depth becomes sufficiently low. We also add a comment on the weakness of the magnetic field of the pulsar in SN 1987A. Since it is apparently weaker than the typical one, it seems to be suggested that the strength of the magnetic field of a newly born pulsar evolves as a function of time. Thus we may be able to observe in the near future the magnetic field of a pulsar growing stronger when we can observe the pulsar activity directly.

Finally, we consider the possibility of radiating gravitational waves to a sufficient extent to explain the observed pulsar spindown. Middleditch et al. (2000) concluded that the required non-axisymmetric oblateness ( $\epsilon$ ) is  $\sim 10^{-6}$ , since a slightly deformed, homogeneous ellipsoidal pulsar with moment of inertia  $I$  and ellipticity  $\epsilon$  radiates energy in the form of gravitational waves at a rate

$$\dot{E}_{\text{GW}} = -\frac{32 G}{5 c^5} I^2 \epsilon^2 \Omega^6. \quad (2.11)$$

Here  $\epsilon$  is defined as

$$\epsilon = \frac{a - b}{(a + b)/2}, \quad (2.12)$$

where  $a$  and  $b$  are the equatorial semiaxes.

We should discuss where and why a non-axisymmetric component of the moment of inertia is realized in a neutron star. Here we have to note that the average density of a pulsar is about  $5 \times 10^{14} \text{ g cm}^{-3}$ . Thus it is meaningless to consider a 'mountain' on the surface of a neutron star, where the density is about  $10^9 \text{ g cm}^{-3}$  and the density scale height is only  $\sim 1 \text{ cm}$ .<sup>15)</sup> This is because the contribution of the mountain on the surface of the neutron star is too little to explain the non-axisymmetric component of the moment of inertia. Rather, we should consider density fluctuation in the inner crust, where the typical density is sufficiently high and the contribution to the moment of inertia is not negligible. In particular, Lorenz et al.<sup>16)</sup> reported that there may be a nuclear 'pasta' at the innermost region of the inner crust.<sup>17)</sup> In this nuclear pasta region, we can easily guess that non-uniform crystallization due to the rapid cooling of the newly born neutron star will result in

such a non-axisymmetric component of the moment of inertia. It is a very important task to estimate the nucleation rate and the growth rate of such a crystal in the pasta region. This should give information on the non-axisymmetric component of the moment of inertia in neutron stars.

### §3. Implications for the jet-like explosion in SN 1987A

Effects of rotation on the dynamics of collapse-driven supernovae have been investigated in many works.<sup>2), 4), 18), 19)</sup> However, the initial rotational energy has been given parametrically in these works, because we have little information on it. Because we now have information on the rotational energy of the newly born pulsar in SN 1987A, we can now carry out further analysis. First, we estimate the initial period of the pulsation. From Eqs. (2·1) and (2·11), the initial period can be estimated as

$$T_i = T_o \left( 1 - 4 \frac{t}{T_{\text{GW}}} \right), \quad (3\cdot1)$$

where  $T_o$ ,  $t$ , and  $T_{\text{GW}}$  are the present period ( $\sim 2.14$  ms), present time  $\sim 5$  yr, and  $-\Omega_o/\dot{\Omega}_o$ , respectively. From Eq. (3·1), the initial period of pulsation can be estimated as (1.9–2.0)ms. Even if we assume that the pulsar spindown is caused by magnetic dipole radiation and/or relativistic pulsar winds, the estimated initial period changes little. Now we can estimate the ratio of the rotational energy relative to the gravitational binding energy at the moment of the core-collapse ( $T/|W|_{\text{init}}$ ). It is estimated as

$$T/|W|_{\text{init}} = \frac{25G}{12c^2} q^2 \left( \frac{M}{R} \right) \quad (3\cdot2)$$

$$\sim 4.3 \times 10^{-3} \left( \frac{M}{1.4M_\odot} \right) \left( \frac{1000 \text{ km}}{R} \right) q^2 \quad (3\cdot3)$$

where  $q = Jc/GM^2 = I\Omega c/GM^2$  is the dimensionless angular momentum. Since the value for  $q$  can be estimated as

$$q = 0.2 \left( \frac{1.4M_\odot}{M} \right) \left( \frac{R}{10 \text{ km}} \right)^2 \left( \frac{2 \text{ ms}}{P} \right), \quad (3\cdot4)$$

$T/|W|_{\text{init}}$  for the progenitor of SN 1987A can be estimated to be  $1.7 \times 10^{-4}$ .

We wish to stress the fact that this estimated value is smaller than the values assumed in the study of Yamada and Sato (1994), in which an extremely deformed shock wave is formed. Thus, it can be easily guessed that a mildly deformed shock wave was formed in the core of SN 1987A. This is consistent with the conclusion reached in Nagataki (2000).

We can also estimate the ellipticity ( $e$ ) of the proto-neutron star in SN 1987A from the rotational energy. Since the relation between  $e$  and  $T/|W|$  can be written as<sup>20)</sup>

$$\frac{T}{|W|} = \frac{3}{2e^2} \left( 1 - \frac{e(1-e^2)^{1/2}}{\sin^{-1} e} \right) - 1, \quad (3\cdot5)$$

$e$  can be estimated as  $\sim 0.25$ . Here we have assumed that the mass and radius of the proto-neutron star are  $1.4M_{\odot}$  and 20 km, respectively. This means that the ratio of the semimajor axis relative to the semiminor axis of the proto-neutron star is  $\sim 1.03$ . It should be noted that this value is smaller than that assumed in the work of Shimizu et al. (1994), in which an extremely deformed shock wave is formed due to the effects of asymmetric neutrino heating from the deformed neutrinosphere. This discussion given here also supports the conclusion reached in Nagataki (2000) that a mildly deformed shock wave is required in order to realize the appropriate matter mixing and explosive nucleosynthesis in SN 1987A.

It is a very important task to perform numerical simulations in which the effects of rotation and neutrino heating are included in order to make an appropriate model for SN 1987A in which a mildly deformed shock wave and a rotating neutron star with a period of 2 ms are formed. Such a model will help us to understand more clearly the system SN 1987A and the roles of rotation and asymmetric neutrino heating on the dynamics of collapse-driven supernovae.

#### §4. Gravitational waves from the pulsar

We can estimate the amplitude of the gravitational waves from the pulsar in SN 1987A. The energy release rate due to the gravitational waves can be written

$$\dot{E} = \frac{c^3}{16\pi G} \Omega^2 \langle h \rangle^2 \times 4\pi D^2, \quad (4.1)$$

where  $\langle h \rangle$  is the average dimensionless amplitude of the gravitational waves at the distance  $D$  from the pulsar. From Eqs. (2.11) and (4.1),  $\langle h \rangle$  can be estimated as

$$\begin{aligned} \langle h \rangle &\sim 5.1 \frac{G}{c^4 D} I \epsilon \Omega^2 & (4.2) \\ &\sim 4.7 \times 10^{-26} \left( \frac{I}{1.1 \times 10^{45} \text{ g cm}^2} \right) \left( \frac{\epsilon}{10^{-6}} \right) \left( \frac{\Omega}{2936 \text{ rad s}^{-1}} \right)^2 \left( \frac{50 \text{ kpc}}{D} \right) & (4.3) \end{aligned}$$

Thus, the required time to detect the gravitational wave from the pulsar using the Fabry-Perot-Michelson interferometer as the gravitational detector is

$$\Delta T = 4.2 \left( \frac{h'}{3 \times 10^{-22} [1/\sqrt{\text{Hz}}]} \right)^2 \text{ [yr]}, \quad (4.4)$$

where  $h'$  is the sensitivity of the detector at  $2 \times 467.5 = 935$  Hz, which has units of  $1/\sqrt{\text{Hz}}$ . We can find that detection of the gravitational wave from the pulsar is possible within a reasonable time when gravitational detectors such as LIGO<sup>21)</sup> and TAMA<sup>22)</sup>, whose sensitivities are of order  $h' \sim 10^{-22} \text{ Hz}^{-1/2}$ , are running.

#### §5. Implications on the kick velocity of a newly-born pulsar

It is a well known fact that pulsars in our galaxy have velocities much greater than those of ordinary stars.<sup>23)</sup> It is reported that their transverse speeds range from 0 to  $\sim 1500 \text{ km s}^{-1}$  and their mean three-dimensional speeds are  $\sim 450 \pm 90 \text{ km s}^{-1}$ .<sup>24)</sup> There are many theoretical models to explain the pulsar kick. According to one, a neutron star in a binary system can escape from the system with rapid speed due to a supernova explosion of the nascent star.<sup>25)</sup> There are also many models in which effects of asymmetric supernova explosions are taken into consideration.<sup>26)</sup> <sup>27)</sup> For example, it is reported that neutrino oscillations, biased by the magnetic field, alter the shape of the neutrino sphere in a cooling proto-neutron star and are the origin of the kick velocity of the pulsar.<sup>27)</sup> In another work, Burrows and Hayes (1996) pointed out the possibility that hydrodynamical instabilities may be the origin of the pulsar kick. However, there are too few observations to determine which model is the most promising one.

It is suggested that the pulsar in SN 1987A also has a kick velocity and is moving toward the south region of the remnant.<sup>28), 29), 4), 30)</sup> As discussed in section 2, it is suggested that the strength of magnetic fields on the surface of the pulsar in SN 1987A is very weak. Therefore it is concluded that a neutrino oscillation model like that of Kusenko and Segrè (1996), which requires magnetic fields of order  $10^{14} \text{ G}$ , is not promising. This is the first investigation with the purpose of selecting the best model of the kick velocity using observational data. We will be able to give further discussion when we obtain more precise data on the pulsar in SN 1987A. We hope there will be further observations of this pulsar at many frequencies of photon and gravitational waves in the near future so that we can continue our investigation and confirm the report of the discovery presented by Middleditch et al. (2000).

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