Implications of the Discovery of Millisecond Pulsar in SN 1987A

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From the observation of the 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 derived in Nagataki (2000). 3) The gravitational waves from the pulsar will be detected in (5-10) years by the Fabry-Perot-Michelson interferometer as the gravitational detector such as LIGO and TAMA. 4) The neutrino oscillation model is not a promising one for the explanation of the kick velocity of the pulsar in SN 1987A. The hydrodynamical instability model will be more favored.

§ 1. Introduction

Since there were few informations on the pulsar in the remnant of SN 1987A, its properties such as its angular velocity of rotation, strength of the magnetic fields, and total baryon mass were treated as free parameters or output parameters¹²³⁴. However, Middleditch et al. (2000) reported the discovery of an optical pulsar whose frequency is 467.5 Hz and spindown rate is (2-3)×10⁻¹⁰ Hz s⁻¹. Since some free parameters in the 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 make 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. Amplitude of the gravitational waves from the pulsar and its detectability are discussed in section 4. Implications on 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 (2-3×10⁻¹⁰ Hz s⁻¹) 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 (δI) to the spherical neutron star whose moment of inertia is I.

It is true that this conclusion seems to be curious, because the spindowns of a normal pulsar is believed to be caused by magnetic dipole radiation⁶ and/or relativistic
pulsar winds\(^7\)). However, we want to emphasize that their conclusion can be supported by the recent UVOIR bolometric light curve. We can easily calculate the decreasing rate of the rotational kinetic energy of the pulsar as
\[
\frac{dE}{dt} \equiv \dot{E} = I \Omega \frac{d\Omega}{dt},
\] (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
\[
I = 1.1 \times 10^{45} \left( \frac{M}{1.4M_\odot} \right) \left( \frac{R}{10\text{km}} \right)^2 [\text{g cm}^2].
\] (2.2)
So, using the observation on \(\Omega\) and \(\dot{\Omega}\), we can estimate \(\dot{E}\) as
\[
\dot{E} = -(4 - 6) \times 10^{39} \left( \frac{M}{1.4M_\odot} \right) \left( \frac{R}{10\text{km}} \right)^2 [\text{erg s}^{-1}],
\] (2.3)
which is much larger than the UVOIR bolometric luminosity, \((1-2) \times 10^{36} \text{ erg s}^{-1}\). This discussion strongly supports that the pulsar spindown is caused by radiating gravitational waves. Otherwise, the supernova remnant will become much brighter.

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

As for the radio emission, it is reported that its spectrum is well fitted as\(^9\)
\[
S \sim 10^{-15} \left( \frac{\nu}{1\text{GHz}} \right)^{-1} [\text{erg s}^{-1} \text{ cm}^{-2} \text{ GHz}^{-1}].
\] (2.4)
Here Gaensler et al.\(^9\) used the data at frequencies of 1.4, 2.4, 4.8, and 8.6 GHz. So, when we assume that this power-law fitting holds at all radio band, we can estimate its luminosity as
\[
L_{\text{radio}} \sim 3 \times 10^{32} \left( \frac{D}{50\text{kpc}} \right)^2 \log_e \left( \frac{\nu_{\text{max}}}{\nu_{\text{min}}} \right),
\] (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\(^10\), we can find that the the luminosity in the radio band is much lower than the decreasing rate of the rotational energy. In fact, unless \(\nu_{\text{min}}\) is as low as \(10^{-1000000}\) Hz, the luminosity in the radio band is not comparable to the decreasing rate of the rotational energy. Moreover, it is generally believed that the radio emission does not come from the pulsar but from the synchrotron emission of electrons that are generated when the shock encounters the circumstellar matter\(^9\).

As for the X-rays, an upper limit of \(2.3 \times 10^{34} \text{ erg s}^{-1} (0.5 - 2 \text{ keV})\) is placed by the Chandra observations of the remnant\(^11\). They also discussed that this low upper limit is not surprising in view of calculation showing that the debris should still be opaque to soft X-rays\(^12\). So we can conclude that the rapid decreasing rate of the rotational energy can not be explained by the emission of the soft X-rays.
As for the hard X-rays and gamma-rays, the remnant is thought to be transparent. In fact, Fransson and Chevalier\(^{12}\) reported that the energy corresponding to absorption optical depth unity of the ejecta can be well represented by the formula

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

(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 \(M_c = 3.7 M_\odot\)\(^3\), \(V_c = 2500 \text{ km s}^{-1}\)\(^4\), and \(t = 5 \text{ yr}\), we can get \(E(\tau = 1) = 40 \text{ keV}\). So the situation is different from the soft X-rays, that is, the remnant is thought to be transparent to the 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 is not new. The gamma-ray continuum on 1989 April 4 can be fit as\(^{13}\)

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

(2.7)

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

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

(2.8)

where \(E_{\max}\) is the maximum energy of the gamma-ray photons. It is generally believed that these gamma-rays come from the radioactive nuclei such as \(^{56}\text{Co}\) and \(^{57}\text{Co}\)\(^{14}\). Moreover, the Crab nebula, whose energy source is the central pulsar, is brightest in X-ray band. So it seems difficult to think that the remnant in SN 1987A is brightest in gamma-ray band and its luminosity can be comparable to the decreasing rate of the rotational energy. In case the total gamma-ray luminosity is turn out to be as high as the decreasing rate of the rotational energy by the future observations, we have to consider a serious problem to produce gamma-rays only. That is, we have to consider the difficult mechanism to produce only gamma-rays and not to produce the photons in other energy bands from the pulsar.

Due to the reasons mentioned above, we think that it is hard to explain the observed spindown by the magnetic dipole model and/or relativistic pulsar wind model. However, it will be necessary to make a strict upper limit of the present gamma-ray flux from SN 1987A in order to derive the complete conclusion that the pulsar spindown is not caused by radiating photons and/or ejecting relativistic particles but by the gravitational waves.

We can also give un 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 decreasing energy rate can be written as\(^7\)

\[
\dot{E} = -\frac{B_p^2 R^6 \Omega^4}{c^3},
\]

(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

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

(2.10)
Since the strength of the magnetic field is so weak, the neutron star without hot spots will be found in X-ray bands in the near future, that is, the surface temperature of the neutron star will be approximately uniform and such a neutron star will 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 lower than the typical value, this fact may suggest that the strength of the magnetic field of the newly born pulsar evolves as a function of time. So we may be able to observe in the near future the magnetic field of the pulsar to be getting stronger and stronger when we can observe the pulsar activity directly.

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

$$\dot{E}_{GW} = -\frac{32}{5} G \epsilon^2 I^2 \omega^6.$$  \hfill (2.11)

Here $\epsilon$ is defined as

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

where $a$ and $b$ are the equatorial semi-axes.

We have to discuss where and why the nonaxisymmetric component of the moment of inertia is attained in a neutron star. Here we have to note that the average density of the pulsar is about $5 \times 10^{14} \text{ g cm}^{-3}$. So it is meaningless to consider the ‘mountain’ on the surface of the neutron star where the density is about $10^9 \text{ g cm}^{-3}$ and the density scale height is only $\sim 1 \text{ cm}^{15}$. Rather, we should consider the density fluctuation in the inner crust where the typical density is sufficiently high and contribution to the moment of inertia is not negligible. In particular, Lorenz et al.\(^\text{16}\) reported that there may be a nuclear ‘pasta’ at the inner most region of the outer crust\(^\text{17}\). At this nuclear pasta region, we can easily guess that the non-uniform crystallization due to the rapid cooling of the newly born neutron star will result in such a nonaxisymmetric component of the moment of inertia. It will be a very important task to estimate the nucleation rate and the growth rate of the crystal at the pasta region, which will give informations on the nonaxisymmetric component of the moment of inertia in a neutron star.

\section*{§3. Implications on the jet-like explosion in SN 1987A}

Effects of rotation on the dynamics of collapse-driven supernovae have been investigated in many works\(^\text{2\div4\div18\div19}\). However, the initial rotational energy has been given parametrically in their works because we have little information on it. Since we got the information on the rotational energy of the newly born pulsar in SN 1987A, we can continue to further discussion.

At first, we estimate the initial period of the pulsation. From Eqs. (2.1) and (2.11),
the initial period can be estimated as

\[ T_i = T_o \left( 1 - 4 \frac{t}{T_{GW}} \right), \]  

(3.13)

where \( T_o, t, \) and \( T_{GW} \) are present period (~ 2.14 ms), present time ~ 5 yr, and \(-\Omega_o/\dot{\Omega}_o\), respectively. From Eq. (3.13), 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 the 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

\[ \frac{T}{|W|_{\text{init}}} = \frac{25G}{12c^2} q^2 \left( \frac{M}{R} \right) \]

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

(3.15)

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

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

(3.16)

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

We want 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. So, it can be guessed easily that a mildly deformed shock wave was formed in the core of SN 1987A, which is consistent with the conclusion derived 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

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

(3.17)

e can be estimated to be \( \sim 0.25 \). Here we 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 \( \sim 1.2 \). 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 neutrino sphere. This discussion also supports the conclusion derived in Nagataki (2000) in which a mildly deformed shock wave is required in order to cause the appropriate matter mixing and explosive nucleosynthesis in SN 1987A.

It will be a very important task to perform the 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 the system SN 1987A more clearly and 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. Energy release rate due to the gravitational waves can be written as

\[ \dot{E} = \frac{c^3}{16\pi G} \Omega^2 \langle h \rangle^2 \times 4\pi D^2, \]  

(4.18)

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 (4.18), \( \langle h \rangle \) can be estimated as

\[ \langle h \rangle \sim 5.1 \frac{G}{c^4 D} I \epsilon \Omega^2 \] 

(4.19)

\[ \sim 7.8 \times 10^{-27} \left( \frac{I}{1.1 \times 10^{45} \text{g cm}^2} \right) \left( \frac{\epsilon}{10^{-6}} \right) \left( \frac{\Omega}{2936 \text{rad s}^{-1}} \right)^2 \left( \frac{50 \text{kpc}}{D} \right). \]  

(4.20)

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

\[ \Delta T = 5.2 \left( \frac{h'}{1 \times 10^{-22} [1/\sqrt{\text{Hz}}]} \right) \text{[yr]}, \]  

(4.21)

where \( h' \) is the sensitivity of the detector at \( 2 \times 467.5 = 935 \text{Hz} \) which has the dimension of \( 1/\sqrt{\text{Hz}} \). We can find that detection of the gravitational wave from the pulsar is never impossible in a reasonable time when the gravitational detectors such as LIGO\(^{21}\) and TAMA\(^{22}\) whose sensitivity is of order \( h' \sim 10^{-22} \text{ Hz}^{-1/2} \) work.

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

It is a well known fact that pulsars in our galaxy have velocities much in excess of those of ordinary stars\(^{23}\). It is reported that their transverse speeds range from 0 to \( \sim 1500 \text{ km s}^{-1} \) and their mean three-dimensional speed is \( 450 \pm 90 \text{ km s}^{-1} \)\(^{24}\).

On the other hand, there are many theoretical models in order to explain the pulsar kick. One is that a neutron star in a binary system can escape from the system with rapid speed due to a supernova explosion of the nascent star\(^{25}\). There are also many models in which effects of asymmetric supernova explosion are taken into consideration\(^{26-27}\). For example, it is reported that neutrino oscillations, biased by the magnetic field, alter the shape of the neutrinosphere in a cooling proto-neutron star and result in the origin of the kick-velocity of the pulsar\(^{27}\). On the other hand, Burrows and Hayes (1996) pointed out the possibility that the hydrodynamical instabilities may be the origin of the pulsar kick. However, there has been few observations to determine which model is the most promising one.

It is suggested that the pulsar in SN 1987A also has kick-velocity and is running toward the south region of the remnant\(^{4-28}\). As discussed in section 2, it is suggested that the strength of the pulsar in SN 1987A is very weak. So it is concluded that the neutrino oscillation model like Kusenko and Segrè (1996) , which requires the magnetic
fields of order $10^{16}$ G, is not a promising one. This is the first discussion to select the model of the kick-velocity using observational data. We will be able to continue to the further discussion when we get more precise data on the pulsar in SN 1987A.

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