Effects of neutrino oscillation on supernova neutrino: inverted mass hierarchy

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(Received )

We study the effects of neutrino oscillation on supernova neutrino in the case of the inverted mass hierarchy ($m_3 \ll m_1 < m_2$) as well as the normal mass hierarchy ($m_1 < m_2 \ll m_3$). Numerical analysis using a realistic supernova and presupernova model allows us to discuss quantitatively a possibility to probe neutrino oscillation parameters. We show that information about the mass hierarchy can be obtained if $\theta_{13}$ is rather large ($\sin^2 2\theta_{13} > 10^{-3}$) and that $\theta_{13}$ can be well probed by SuperKamiokande if the neutrino mass hierarchy is the inverted case. Errors due to the uncertainty of the original neutrino spectra and the Earth effect are also discussed.

§1. Introduction

Neutrino mixing and mass spectrum are the keys to probe new physics beyond the standard model of particle physics. Some of the neutrino oscillation parameters have been revealed dramatically by the observation of the atmospheric neutrino\cite{1} and the solar neutrino\cite{2}-\cite{6}. Recently the first results of the KamLAND experiment have confirmed the Large Mixing Angle (LMA) solution of the solar neutrino problem \cite{7}. An upper bound on $\theta_{13}$ has also been obtained from CHOOZ experiment \cite{8} and a lower bound is expected to obtained from single and double beta decay experiments \cite{9}. But there still remain some ambiguities in the properties of neutrinos: the mass hierarchy, i.e., normal or inverted and the magnitude of $\theta_{13}$. Current status is reviewed by many authors\cite{10}-\cite{13}.

In such present situation, much attention have been paid to another neutrino source, supernova. This is a completely different system from sun, atmosphere, accelerator, and reactor in regard to neutrino energy, flavor of produced neutrinos, propagation length and so forth. Then neutrino emission from a supernova is expected to give valuable information that can not be obtained from neutrinos from other sources. In fact, pioneering observations of neutrinos from SN1987A\cite{14},\cite{15} contributed significantly to our knowledge of the fundamental properties of neutrinos\cite{16}-\cite{18}. Especially there have been many studies about the implication for the mass hierarchy from the observed neutrino events and the inverted hierarchy is disfavored if $\sin^2 \theta_{13}$ is rather large ($> 10^{-4}$)\cite{19}-\cite{21}. Here, normal and inverted mass hierarchies are the mass pattern $m_3 \gg m_2 > m_1$ and $m_2 > m_1 \gg m_3$, respectively. In our notation $\Delta m^2_{ij} = m^2_j - m^2_i$, $\Delta m^2_{12}$ and $\Delta m^2_{13} \sim \Delta m^2_{23}$ are the mass squared differences which are related with the solutions of the solar and atmospheric neutrino
problems, respectively. There have also been studies to try to extract the unknown neutrino properties from future supernova \(^{22}) - ^{27}\).

In this paper, we calculate numerically the effects of neutrino oscillation on supernova neutrino, extending our previous study \(^{27}\) where all analyses are performed with normal mass hierarchy, and investigate the possibility to identify the mass hierarchy and to probe the neutrino oscillation parameters \(\theta_{13}\) by the observation of the neutrinos from the next galactic supernova. We use the original neutrino spectra from supernova based on a realistic supernova model and the density profile of the progenitor star based on a realistic presupernova model. Since uncertainties of the original neutrino spectra are important in this analysis, we estimate the effect of them on our analysis. The Earth matter effect is also discussed, which have already been studied in the case of normal hierarchy in our previous papers \(^{29}), ^{30}\).

This paper is organized as follows. In section II we summarize the properties of supernova neutrino briefly. The method of analysis is described and the results are shown in section III. We discuss some ambiguities in the basis of our study and summarize our results in section IV.

\section*{§2. Supernova Neutrino}

Here we summarize the properties of supernova neutrino. For details, see, for example, a review by Suzuki \(^{34}\). Almost all of the binding energy of the neutron star,

\[ E_b \simeq \frac{G M_{NS}^2}{R_{NS}} \simeq 3 \times 10^{53} \text{erg} \left( \frac{M_{NS}}{M_\odot} \right)^2 \left( \frac{10 \text{km}}{R_{NS}} \right), \]

(2.1)
is radiated away as neutrinos. Here \( G, M_{NS} \) and \( R_{NS} \) are the gravitational constant, the mass and radius of the neutron star, respectively. Due to the difference of interaction strength, average energies are different between flavors. Although quantitative estimate of the difference is difficult, it is qualitatively true that \( \langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle \). Here \( \nu_x \) means \( \nu_\mu, \nu_\tau \) and their antineutrinos. These differences are essential in this paper.

We use a realistic model of a collapse-driven supernova by the Lawrence Livermore group \(^{36}\) to calculate the neutrino luminosities and energy spectra, as we did in our previous paper \(^{27}\). The average energy of each flavor is:

\[ \langle E_{\nu_e} \rangle \simeq 13 \text{MeV}, \quad \langle E_{\bar{\nu}_e} \rangle \simeq 16 \text{MeV}, \quad \langle E_{\nu_x} \rangle \simeq 23 \text{MeV}. \]

(2.2)

Details of this original neutrino spectra are discussed by Totani et al. \(^{37}\) These neutrinos, which are produced in the high dense region of the iron core, interact with matter before emerging from the supernova. Due to the nonzero masses and the mixing in vacuum among various neutrino flavors, flavor conversions can occur in supernova. When the mixing angle is small, these conversions occur mainly in the resonance layer, where the density is

\[ \rho_{\text{res}} \simeq 1.4 \times 10^{6} \text{g/cc} \left( \frac{\Delta m^2}{1 \text{eV}^2} \right) \left( \frac{10 \text{MeV}}{E_{\nu}} \right) \left( \frac{0.5}{Y_e} \right) \cos 2\theta, \]

(2.3)
where $\Delta m^2$ is the mass squared difference, $\theta$ is the mixing angle, $E_\nu$ is the neutrino energy, and $Y_e$ is the mean number of electrons per baryon. Since the supernova core is dense enough, there are two resonance points in supernova envelope. One that occurs at higher density is called H-resonance and another is called L-resonance. If the mass hierarchy is normal, both resonances occur in neutrino sector. On the other hand, if the mass hierarchy is inverted, H-resonance occurs in antineutrino sector and L-resonance occurs in neutrino sector. The schematic level crossing diagram for normal and inverted mass hierarchies are shown in Fig. 1.

The dynamics of conversions including large mixing case is determined by the adiabaticity parameter $\gamma$, which depend on the mixing angle and the mass-squared difference between involved flavors:

$$\theta_{13} \text{ and } \Delta m^2_{13} \text{ at H - resonance,}$$

$$\theta_{12} \text{ and } \Delta m^2_{12} \text{ at L - resonance.}$$

When $\gamma \gg 1$, the resonance is called 'adiabatic resonance' and the fluxes of the two involved mass eigenstate are completely exchanged. On the contrary, when $\gamma \ll 1$, the resonance is called 'nonadiabatic resonance' and the conversion does not occur. The dynamics of the resonance in supernova is studied in detail by Dighe and Smirnov $^{22}$. "

§3. Method and Results

In this section we describe the method of analysis and show the results.

3.1. Conversion Probabilities

In the framework of three-flavor neutrino oscillation, the time evolution equation of the neutrino wave functions can be written as follows:

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = H(t) \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix},$$

Fig. 1. Schematic level crossing diagram for normal (left) and inverted (right) mass hierarchies. The circles shows the resonance points.
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\begin{equation}
H(t) \equiv U \begin{pmatrix}
0 & 0 & 0 \\
0 & \Delta m_{12}^2/2E_\nu & 0 \\
0 & 0 & \Delta m_{13}^2/2E_\nu
\end{pmatrix} U^{-1} + \begin{pmatrix}
A(t) & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}, \tag{3.2}
\end{equation}

where \(A(t) = \sqrt{2}G_F n_\nu(t)\), \(G_F\) is Fermi constant, \(n_\nu(t)\) is the electron number density, and \(\Delta m_{ij}^2\) is the mass squared differences. In case of antineutrino, the sign of \(A(t)\) changes. Here \(U\) is the Cabibbo-Kobayashi-Maskawa (CKM) matrix:

\begin{equation}
U = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13}
\end{pmatrix}, \tag{3.3}
\end{equation}

where \(s_{ij} = \sin \theta_{ij}, c_{ij} = \cos \theta_{ij}\) for \(i, j = 1, 2, 3(i < j)\). We have here put the CP phase equal to zero in the CKM matrix.

By solving numerically these equations along the density profile of progenitor, which is calculated by Woosley and Weaver \cite{30}, we obtain conversion probabilities \(P(\alpha \rightarrow \beta)\), i.e., probability that \(\nu_\alpha\) at the center of the supernova becomes \(\nu_\beta\) at the surface of the progenitor star.

In our previous paper \cite{27}, we assumed the normal mass hierarchy and took four models for neutrino oscillation parameters, the differences being the solution of the solar neutrino problem (LMA or SMA) and the magnitude of \(\theta_{13}\). Here we take the following values:

\begin{align}
\sin^2 2\theta_{12} &= 0.84, \quad \Delta m_{12}^2 = 7 \times 10^{-5}\text{eV}^2,
\sin^2 2\theta_{23} &= 1.0, \quad \Delta m_{23}^2 = 3.2 \times 10^{-3}\text{eV}^2. \tag{3.4}
\end{align}

Values of \(\theta_{12}\) and \(\Delta m_{12}^2\) are taken from the global analysis of the solar neutrino observations and the KamLAND experiment \cite{40} and correspond to the LMA solution of the solar neutrino problem while those of \(\theta_{23}\) and \(\Delta m_{23}^2\) are taken from the analysis of the atmospheric neutrino observation \cite{1}. As to \(\theta_{13}\), we take two fiducial values \(\sin^2 2\theta_{13} = 0.043, 10^{-6}\) as we did in our previous paper \cite{27}. Later we will discuss the case of the other values. Furthermore, we consider both normal and inverted hierarchy. Consequently, there are four models and we call them normal-LMA-L, normal-LMA-S, inverted-LMA-L and inverted-LMA-S. The last character (L or S) represents the magnitude of \(\theta_{13}\) (large or small). In our notation, \(\Delta m_{ij}^2 = m_j^2 - m_i^2\) so that \(\Delta m_{13}^2 > 0\) in the normal hierarchy case and \(\Delta m_{13}^2 < 0\) in the inverted hierarchy case. Therefore, normal-LMA-L and inverted-LMA-L are different only in the sign of \(\Delta m_{13}^2\).

We show in Fig. 2 demonstrations of conversion probabilities. The left figure is the time evolution of \(P(e \rightarrow e)\), probability that \(\nu_e\) remains \(\nu_e\), and the right figure is that of \(P(\bar{e} \rightarrow \bar{e})\), probability that \(\bar{\nu}_e\) remains \(\bar{\nu}_e\). Four curves for the same model correspond to the neutrino of energy, 5 MeV, 10 MeV, 40 MeV and 70 MeV, respectively. It can be seen that H-resonance and L-resonance occur at the O+Ne+Mg and He layer, respectively. In the neutrino sector, the conversion probabilities for the inverted hierarchy are the same as those for the model normal-LMA-S. This is because the H-resonance is completely nonadiabatic when \(\theta_{13}\) is very
small, as in normal-LMA-S, and this is phenomenologically as if the H-resonance is absent as in the inverted hierarchy case. This logic also applies to why normal-LMA-L, normal-LMA-S and inverted-LMA-S are degenerate in the antineutrino sector, if we consider the H-resonance in the antineutrino sector. These degeneracies are the origins of the degeneracies that appear later in the event rates.

3.2. Event Rates

After obtaining the conversion probabilities, the neutrino fluxes at the Earth are calculated by multiplying the conversion probabilities by the original spectra and the distance factor $1/4\pi d^2$. Here we take 10 kpc for the distance $d$ between the Earth and the supernova. Further, by multiplying these fluxes by the cross sections of the detection interactions, the detector volume and the detector efficiency, we obtain the event rates at the detectors. Here we consider two detectors: SuperKamiokande (SK) and SNO. Properties of these detectors and cross sections used to calculate event rates are described in our previous paper.27) Unfortunate accident at SK lessened the detection efficiency at low energy ($< 8$ MeV) but this cause negligible effect in the subsequent analysis.

Fig. 3 - 5 show the time-integrated energy spectra (left) and the time evolution of the number of neutrino events (right) at SK and SNO ($\nu_e$ charged current (CC) events and $\bar{\nu}_e$ CC events), respectively. In Fig. 3, only $\nu_{e}p$ CC interaction is taken into account. Event numbers of each interaction are shown in Table I and II. In these tables, the contribution from neutronization burst phase is also shown. Here the neutronization burst phase means the period from 41msec to 48msec after the bounce.

3.3. Distinction between Models

In general neutrino oscillation makes the $\nu_e$ and $\bar{\nu}_e$ spectra harder, since the original average energies of $\nu_e$ and $\bar{\nu}_e$ are smaller than that of $\nu_x$. In other words neutrino oscillation produces high energy $\nu_e$ and $\bar{\nu}_e$ from $\nu_x$. As a result, the high-energy events increase and the low-energy events decrease. The boundary between

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**Fig. 2.** Time evolution of conversion probabilities $P(e \to e)$ and $P(\bar{e} \to \bar{e})$. Four lines of the same marking correspond to neutrino energy, 5MeV, 10MeV, 40MeV, and 70MeV, respectively.
Fig. 3. The time-integrated energy spectra (left) and the time evolution of the number of neutrino events (right) at SK. In these figures, only $\bar{\nu}_e p$ CC interaction is taken into account.

Fig. 4. The time-integrated energy spectra (left) and the time evolution of the number of neutrino events (right) at SNO. In these figures, only $\nu_e d$ CC interaction is taken into account.

Fig. 5. The time-integrated energy spectra (left) and the time evolution of the number of neutrino events (right) at SNO. In these figures, only $\bar{\nu}_e d$ CC interaction is taken into account.

high energy and low energy is around 20 MeV. Note that how much these increase and decrease are depends on the adiabaticity parameters, and then the neutrino oscillation parameters, as can be seen in Fig. 3, 4 and 5. This feature can be used as a criterion of the magnitude of the neutrino oscillation effects. We define the
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Table I. Number of events at SK

| hierarchy model | normal | inverted | no osc |
|----------------|--------|----------|--------|
| νeνp           | 9459   | 12269    | 8036   |
| νe⁺e⁻          | 186    | 171      | 132    |
| νμ⁺e⁻          | 46     | 56       | 42     |
| ντ⁺e⁻          | 25     | 27       | 30     |
| νe⁻e⁻          | 24     | 12       | 24     |
| ννe             | 297    | 297      | 31     |
| Oνe             | 160    | 296      | 92     |
| total           | 10245  | 13084    | 8441   |
| burst           | 15.7   | 20.1     | 12.4   |

Table II. Number of events (CC) at SNO

| hierarchy model | normal | inverted | no osc |
|----------------|--------|----------|--------|
| νeνd (CC)      | 237    | 185      | 68     |
| ννe             | 118    | 190      | 82     |
| total           | 355    | 375      | 150    |
| burst           | 0.6    | 1.1      | 2.1    |

following ratios of high-energy to low-energy events at both detectors:

\[ R_{SK} \equiv \frac{\text{number of events at } 20 < E < 70\text{MeV}}{\text{number of events at } 5 < E < 20\text{MeV}}, \]

\[ R_{SNO} \equiv \frac{\text{number of events at } 20 < E < 70\text{MeV}}{\text{number of events at } 5 < E < 20\text{MeV}}. \]

Note that the energy range for the definitions of \( R_{SK} \) and \( R_{SNO} \) are different from those in the previous paper \(^{27}\). The plots of \( R_{SK} \) vs \( R_{SNO} \) are shown in Fig. 6. In the left figure, we consider only νeνd CC events at SNO for \( R_{SNO} \) assuming νeνd CC event and ννeνd CC event can be distinguished completely. On the other hand, in the right figure we assume that νeνd CC event and ννeνd CC event can not be distinguished at all and we sum νeνd CC events and ννeνd CC events for \( R_{SNO} \). The error bars represent the statistical errors.

Note that \( νe \) flux and \( ννe \) flux have essentially different information about the neutrino oscillation parameters. For example, inverted-LMA-L and inverted-LMA-S are distinguishable from ννe events but are not from νe events. So it is more effective to distinguish between models if νeνd CC events and ννeνd CC events at SNO can be distinguished perfectly. This can be clearly seen in Fig. 6. In the left figure it is easier to distinguish between normal-LMA-L and (normal-LMA-S and inverted-LMA-S) than in the right figure. But even in the left figure, it may be difficult to distinguish between normal-LMA-L and (normal-LMA-S and inverted-LMA-S) considering some ambiguities discussed in the following sections.
3.4. Uncertainties in the original spectra

One of the crucial ingredients in this study is the flavor-dependences of the original spectra. Smaller differences will make it more difficult to distinguish between various models. There have been many numerical simulations of core collapse but the predicted luminosities and temperatures of neutrinos are different from group by group. Numerical model by the Livermore group \cite{36}, adopted in this paper, has the great advantage that it covers the full evolution of supernova: from the core collapse over the explosion to the cooling phase of the protoneutron star, although it involves rather traditional treatments of neutrinos.

There are simulations with more sophisticated treatments of neutrinos but they do not obtain explosions and neutrino fluxes for only less than 1 sec are available now \cite{41, 42}. These simulations predict less average-energy differences between flavors compared to those of the Livermore group: $E_x/E_\nu \sim 1.4$ \cite{41}, $1.7$ \cite{42}, $E_x/E_{\bar{\nu}} \sim 1.1$ \cite{41}, $1.3$ \cite{42}, where $E_\nu$, $E_{\bar{\nu}}$ and $E_x$ are the average energies of $\nu_\alpha$, $\bar{\nu}_\alpha$ and $\nu_x$, respectively. To see the effect of the uncertainties in the temperature differences on our analysis, we perform similar analyses varying $\nu_x$ temperature as stated below and fixing $\nu_\alpha$ and $\bar{\nu}_\alpha$ temperatures. This is relevant because various simulations agree well with respect to $\nu_\alpha$ and $\bar{\nu}_\alpha$ temperatures. The original spectra can be fitted by the “pinched” Fermi-Dirac distribution,

$$f(E, T_\alpha, \eta_\alpha) \propto \frac{E^2}{e^{E/T_\alpha - \eta_\alpha} + 1},$$

where the temperature $T_\alpha$ and the pinching parameter $\eta_\alpha$ for each flavor ($\alpha = e, \bar{\nu}$ and $x$) are

$$T_\alpha, \eta_\alpha = (2.8\text{MeV}, 2.6) \text{ for } \nu_e,$$
$$\phantom{=} (4.0\text{MeV}, 2.5) \text{ for } \bar{\nu}_e,$$
$$\phantom{=} (7.0\text{MeV}, 0) \text{ for } \nu_x.$$  

We consider the following transformation of the distribution function of $\nu_x$ which
Fig. 7. Temperature ratio dependence of the event ratio at SNO and SK. $T_x/T_e$ vs $R_{SNO}$ in the left and $T_x/T_{\bar{e}}$ vs $R_{SK}$ in the right. In the left figure, only $\nu_e$ events are considered. The errorbars show statistical errors only.

3.5. Dependence on $\theta_{13}$

So far we have considered only two extreme cases: H-resonance is perfectly adiabatic and nonadiabatic. It is interesting to investigate the intermediate cases. In Fig. 8 we show $\theta_{13}$ dependence of $R_{SK}$ and $R_{SNO}$. Only $\nu_e$ events are taken into account to calculate $R_{SNO}$. Note that $R_{SK}$ and $R_{SNO}$ vary only in the case of inverted and normal hierarchy, respectively, as will be expected from Fig. 6. In the case of normal hierarchy it will be difficult to determine the value of $\theta_{13}$ due to large statistical errors but will be possible to say whether it is very large or very small.
On the other hand, in the case of inverted hierarchy the overlap of the errorbars are small even in the intermediate cases. If $\theta_{13}$ is rather large ($\sin^2 2\theta_{13} > 10^{-3}$) the mass hierarchy will be identified.

3.6. Earth Effects

Depending on the detector position, neutrino go through the Earth and the matter effect inside the Earth can change the neutrino spectra again. For the matter density of the Earth, neutrino oscillation between only two light neutrinos is involved. Since the oscillation length in the Earth, which depends on the neutrino energy, is the same order as the Earth radius for the neutrino parameter adapted here, the Earth matter effect appear as a distosion in the spectra\(^{29)}-^{33)}.

The numerical process to calculate the Earth effect is the same as described above except that the density profile of the Earth is needed. We use a realistic density profile\(^{43)}$. In Fig. 9 neutrino spectra in the case that the nadir angle is $30^\circ$ and $70^\circ$ are shown with that in absence of the Earth effects. The left figure is the $\nu_e$ spectra at SNO and the right figure is the $\bar{\nu}_e$ spectra at SK. The Earth effect is absent in $\nu_e$ and $\bar{\nu}_e$ in case of normal-LMA-L and inverted-LMA-L, respectively. This is because in these cases H-resonance is perfectly adiabatic and low-energy neutrinos, which were originally $\nu_e$ in the supernova core, are converted to the heaviest neutrino, which is not involved in the matter oscillation in the Earth. Thus the detection of the Earth effect will be helpful to distinguish models, especially normal-LMA-L from normal-LMA-S and inverted-LMA-S.

The form of the distorted spectra depends on the nadir angle of the neutrino path. The nadir angle $30^\circ$ and $70^\circ$ correspond to one of the path with which neutrino pass through core and mantle, and only mantle, respectively. The detectability of the Earth effect was discussed by us\(^{30)}$ and it is shown that complementary observation by SK, SNO and Large Volume Detector (LVD) is effective for its detection.
§4. Discussion and Conclusion

There are some ambiguities besides those discussed above. The first is the direction of the supernova. If the supernova can be observed optically, the direction can be known with enough accuracy. But if the supernova is at the Galactic Center, it might be hidden by the large amount of gas and could not be seen optically. Pointing by the electron scattering events of the supernova neutrino is studied by several authors\cite{44, 45} and the accuracy is expected to be $\sim 7^\circ$. More detailed analyses of the Earth effects have been studied considering the locations of the detectors and the direction of the supernova\cite{30, 32}.

Another is the mass of the progenitor star. It affects the mass of the iron core, which affects the neutrino spectra\cite{42, 46, 47}. Study including the mass uncertainty is now in progress but the preliminary result is that the mass uncertainty is not important in our analysis\cite{48}.

Recently effects of shock propagation on neutrino oscillation in supernova have been studied\cite{49, 50, 24, 51} and it was shown that some characteristic signatures may emerge as the shock propagates through the regions where matter-enhanced neutrino flavor conversion occurs. As we show\cite{50}, shock propagation effect will be safely removed by taking only early-phase events into account.

We studied the effects of neutrino oscillation on supernova neutrino in the case of the inverted mass hierarchy as well as the normal mass hierarchy. Numerical analysis using a realistic supernova and presupernova model allowed us to discuss quantitatively a possibility to probe neutrino oscillation parameters. We showed that degeneracy exists only between normal-LMA-S and inverted-LMA-S if the Earth effect is taken into account and that $\theta_{13}$ can be well probed by SK if the neutrino mass hierarchy is inverted case. Errors due to the uncertainty of the original neutrino spectra are also estimated.
§5. Acknowledgments

K.T.’s work is supported by Grant-in-Aid for JSPS Fellows. K.S.’s work is supported by Grant-in-Aid for Scientific Research (S) No. 14102004 and Grant-in-Aid for Scientific Research on Priority Areas No. 14079202.

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