New vision of problem of Geoneutrinos and Earth heat fluxes

L. B. Bezrukov[1], A.S. Kurlovich[1], B. K. Lubsandorzhiev[1], A. K. Mezhokh[1], V.P. Morgalyuk[2], V. V. Sinev[1],*, and V. P. Zavarzina[1]

[1] Institute for Nuclear Researches of Russian Academy of Sciences, Prospekt 60-letia Oktyabrya 7a, 115409 Moscow, Russia, vsinev@inr.ac.ru

[2] A. N. Nesmeyanov Institute of Organoelement Compounds of Russian Academy of Sciences, Vavilova 10, 115409 Moscow, Russia

Abstract The Hydride Earth model predictions of geoneutrino flux and intrinsic Earth heat flux are discussed. The geoneutrino flux predicted by the model can be adjusted to the experimental one. The predicted intrinsic Earth heat flux is significantly larger than model dependent experimental value obtained under assumption that the main heat transfer mechanism is a thermal conductivity. We introduce an additional mechanism of heat transfer in the Earth's crust, namely the energy transfer by hot gases produced in the Earth crust at great depths. The experimental data supporting this idea, in particular the temperature profiles measured in the Kola super deep borehole, are discussed.

Keywords: Earth heat flux, geoneutrinos

1. Introduction

So far there are only two detectors, Borexino [1] and KamLAND [2], which reported registration of geoneutrino signals. Geoneutrinos are electron antineutrinos produced in beta-decays of radioactive elements in natural families of ^{238}U, ^{232}Th and ^{40}K, accumulated inside the Earth. Geoneutrino flux on the Earth surface depends on the amounts of ^{238}U, ^{232}Th and ^{40}K in the Earth and their distribution with the depth.

Amounts of ^{238}U, ^{232}Th and ^{40}K in the Earth and their distribution are different in existing models of the Earth. The theory most popular at the moment is called the Bulk Silicate Earth (BSE) [3, 4]. Its main idea is that element abundances are the same as in meteorites. Based on this idea the amounts of ^{238}U, ^{232}Th and ^{40}K were obtained for the Earth:

$$M_{\mathrm{BSE}}(\mathrm{U}) = 0{,}81\cdot 10^{17}\ \mathrm{kg},\ M_{\mathrm{BSE}}(\mathrm{Th}) = 3{,}16\cdot 10^{17}\ \mathrm{kg\ and}\ M_{\mathrm{BSE}}(^{40}\mathrm{K}) = 5{,}73\cdot 10^{16}\ \mathrm{kg}. \quad (1)$$

These masses are distributed mainly in the Earth crust and partially in its mantle, but they are absent in its core. Experimentally observed antineutrino flux is in agreement with ^{238}U and ^{232}Th amounts from (1) under the assumption that they are distributed in the crust and in the upper mantle [1] only.

Each radioactive decay accompanied by a definite thermal energy emission. If we know the total amounts of ^{238}U, ^{232}Th and ^{40}K in the Earth, the value of radiogenic heat flux can be predicted and it can be compared with experimentally measured one.

The Earth thermal flux on continents in boreholes is explored by the measurement of the temperature gradient at depths of ~500 meters. The thermal flux in oceans is measured by dedicated apparatus which penetrates to the bottom floor by several meters and measures the temperature gradient. To calculate the value of thermal flux one uses the idea that the main thermo-transfer mechanism is a thermal conductivity. Presently the value obtained from experimental measurements assuming the foregoing point of view is 47±2 TW.

The calculated inner Earth thermal flux appears to be equal to 17.5 TW. In this calculation the total masses of ^{238}U, ^{232}Th and ^{40}K in the Earth were taken from (1). Comparison of this value with experimental one did not confirm correctness of the BSE basic assumptions. Researches started to look for additional heat sources.

In this paper we will use an alternative Earth model, so called the Hydride Earth model (HE) [5], and discuss how predictions of geoneutrino and thermal fluxes are correspond to the observed data.

2. Hydride Earth model and geoneutrinos

The main idea of the HE model is the following: a planet element composition depends on the distance from the Sun. That is why the Earth's element composition should differ from composition of asteroids in the asteroid belt which is the source of meteorites. Vladimir Larin [5] proposed and used for element composition calculations the following equation:

$$(X_M/X_{Si})_{Earth} = (X_M/X_{Si})_{Sun} \cdot F(E_{IP}(M)), \qquad (2)$$

where X_M – the share of element M in the Earth mass, X_{Si} – the share of Silicon in the Earth mass, $F(E_{IP}(M))$ – the mass share of chemical element M from the mass of this element in the Sun that existed at the Earth's orbit at its formation, $E_{IP}(M)$ – the ionization potential of element M.

In [6] the function F was proposed as an exponential one [6]:

$$F(E_{IP}(M)) = A\cdot \exp\{- B\cdot E_{IP}(M)\}, \qquad (3)$$

where coefficients A and B were chosen from the known element composition of the Sun and Earth's crust.

We can estimate the total masses of ^{238}U, ^{232}Th and ^{40}K in the Earth using a method of calculation proposed in [7] and quoting the value of $E_{IP}(M)$ and function $F(E_{IP}(M))$ from [8] and [6] respectively:

$$M_{HE1}(U) = 3{,}18\cdot10^{17}\text{ kg},\ M_{HE1}(Th) = 1{,}0\cdot10^{18}\text{ kg and } M_{HE1}(^{40}K) = 2{,}6\cdot10^{19}\text{ kg} \qquad (4)$$

It is noteworthy that the use of function $F(E_{IP}(M))$ as in [6] results in the values of ^{238}U and ^{232}Th masses roughly three times less than in (4) - $M_{HE}(U) = 1{,}1\cdot10^{17}$ kg, $M_{HE}(Th) = 3{,}6\cdot10^{17}$ kg.

As it is shown above, predictions of the HE model depends strongly on the $F(E_{IP}(M))$ function, which is known in its turn rather crudely. It is of fundamental importance that the HE model leaves room for larger values of the total masses of ^{238}U, ^{232}Th and ^{40}K in the Earth as well as allows considering ^{238}U, ^{232}Th and ^{40}K present in the Earth core in the primordial amount, i.e. at the moment of the Earth formation. In particular the total mass of potassium is much more than predicted by the BSE model because of its small ionization potential.

In our previous paper [9] an attempt was done to estimate the maximal values of ^{238}U, ^{232}Th and ^{40}K masses in the Earth which are allowed by the modern experimental data on geoneutrino fluxes and the Earth thermal flux. Our analysis provided the following results:

$$M_{HE2}(U) = 1{,}7\cdot10^{17}\text{ kg},\ M_{HE2}(Th) = 6{,}7\cdot10^{17}\text{ kg and } M_{HE2}(^{40}K) = 1{,}2\cdot10^{19}\text{ kg}. \qquad (5)$$

In the estimates we expanded potassium abundance known for the Earth's crust to the Earth whole volume.

Comparing estimates made by the HE and BSE models, (5) and (1) respectively, one can conclude that they are rather close, although the HE values are slightly larger.

Taking into account that the HE model predicts the total masses of ^{238}U, ^{232}Th and ^{40}K in the Earth's core in primordial abundances experimental arrays for ^{238}U and ^{232}Th geoneutrino flux detection should have substantially larger events statistics in comparison with the present arrays in order to have capabilities to distinguish those two models.

The total mass of ^{40}K predicted by the HE model is more than two orders of magnitude larger than the mass predicted by BSE model. In [10] the capability to detect the large geoneutrino flux due to ^{40}K flux by modern detectors was analyzed. The conclusion is done that sensitivity of presently operating detectors is not sufficient for such a purpose. But for next generation detectors with significantly lower background and larger target possibility to measure geoneutrino flux due to ^{40}K should be conspicuously high. It is also important to have independent measurements of CNO cycle neutrinos spectrum, which is rather close to the spectrum shape of ^{40}K neutrinos.

3. Hydride Earth model and thermal flux of the Earth

One can calculate steady thermal flux of the inner Earth heat knowing the value of the heat energy released per radioactive decay. Thermal flux corresponding to the foregoing mass values of ^{238}U, ^{232}Th and ^{40}K in case of the HE model (5) turns out to be 304 TW. This huge amount of heat is the consequence of the larger amount of potassium in the Earth predicted by the HE model.

At first glance, comparison of the HE value with the experimentally measured one of 47 TW leads to the idea that the HE model is wrong. Indeed, the large amount of potassium follows from the basic HE postulates claiming that ionization potential determines a share of chemical element mass which existed in a planet's orbit at the moment of its formation. If to assume that the HE model is correct than it is necessary to bring forward arguments allowing understanding of so large difference between values of thermal fluxes predicted by the HE model and measured experimentally in boreholes by the temperature gradient method.

Furthermore let's consider here the experimental data of the Earth thermal flux different from the value in 47 TW.

The results of the temperature profile measured in super deep boreholes are rather easy to understand in the framework of the HE model. But, on contrary, the results were not predicted by the BSE model at all.

Scientific results of the Cola super deep borehole were published in [11]. The depth of 12 262 meters was achieved there. In fact all ideas of the Earth's core structure obtained from the measurements in the borehole were inconsistent with expectations. With the deepening the rocks do not get denser and their porosity does not decrease as it was expected earlier. On the contrary, the rocks at the multi-kilometer depth are penetrated by multiple pores and broken by cracks.

It was a sensation that there existed hydrogen and hydrogen-containing gases, in particular water, at high depth where the pressure reaches hundreds of atmospheres.

Finally, it appeared that the Earth is significantly hotter than it was assumed earlier. At the depth of 5 km the temperature exceeds 70°C and passes 120°C and 220°C at 7 km and 12 km depths respectively. The latter is 100°C more than the temperature extrapolated from the value measured at 1 km depth.

The HE model predicts element composition of the primordial Earth. Hydrogen should constitute about 18% of mass and it could be accumulated in the hydride form. Radiogenic heating of the Earth's core results in the production of free hydrogen at the border between the core and mantle. The HE model predicts existence of degasification processes from the Earth's surface, basically by hydrogen containing gases, e.g. water vapor. Gases should be produced at high depth where appropriate temperatures could exist. The gases provide production of multiple cracks and pores in rocks at high depth.

These gases could be the main carrier of thermal energy. Cracks and pores allow gases to move up to the surface. The heat could bypass the thermometers measuring the temperature gradient at the depths of about 500 meters or at the ocean bottom by two ways. The first one is absorption of thermal energy during gas production process. Thermal energy is transferred to the internal energy of gas molecules which is released later by exothermic decomposition reactions at small depths. The second one is transfer of thermal energy to the Earth surface by narrow jets of hot gases. These jets should have substantial distances between them. Existence of such vertical jets leads at large depths to the emergence of horizontal component of gas velocity. Therefore, only a fraction of heat at the depths of about 500 meters takes part in the process of vertical heat transfer by thermo-conductivity mode. The most part of heat energy is carried out by hot gases. We note that boreholes do not drilled at outlets of gas jets because on continental platforms gas outlets look like lakes or swamps. Volcanoes are gas outlets too.

The existence of the forgoing heat transfer mechanism, additional to thermo-conductivity, allows an understanding of unexpected high temperatures at large depths. It also helps to resolve contradiction between the large heat flux predicted by the HE model and results of temperature gradient measurements.

The ARGO experiment published recently interesting results showing temperature increasing of the world ocean in 2005–2010 [12]. Despite that period has been the period of the minimum of solar activity, the world ocean has been warming up. To provide such heating there is a need to have additional energy flux of 0.58 ± 0.15 $W \cdot m^{-2}$ for 6 years. If to multiply this value by the Earth surface area we will get the Earth thermal flux of 300 ± 80 TW.

In the context of the HE model, this experimental fact could be explained by an increase of gases outcome into the ocean and existence of exothermic reactions with gases in the ocean volume. The model includes an idea that the gas flux is not stable but cyclic. We can consider the present ocean heating is observed due to an increase of the Earth's internal heat flux during of the Earth's exit from the small ice age. The value of the heat flux necessary for the observed ocean heating does not cause surprise in frame of the HE model.

It is noteworthy to mention studies done at the Lebedev Physical Institute of the Russian Academy of Sciences (LPI) [13]. In that study the Moon thermal flux was measured by detection of radio wave emission from the Moon. The authors of the paper consider that the heat flux comes from deep interior of the Moon and has the same radiogenic nature as on the Earth. Basing on the idea that the Moon and Earth have the same element composition we can calculate the Earth heat flux using some scaling factor:

$$H_{\mathrm{earth}} = H_{\mathrm{moon}} \cdot M_{\mathrm{earth}} / M_{\mathrm{moon}} = 170 \text{ TW}. \qquad (6)$$

Where: H_{moon} – the measured heat flux at the Moon, M_{earth} and M_{moon} – the Earth and Moon masses respectively. It is necessary to note that on the Moon, according to the HE model, degasification process finished because of its small size and practically all radiogenic energy comes out of the Moon by thermo-conductivity way. The heat flux value calculated using (6) supports the correctness of the HE model. It is important to note that the Moon thermal flux measurements by the radio wave emission method average the Moon thermal flux on the visible Moon surface and gives us the mean value.

In two different points on the Moon surface measurements of thermal flux were done by drilling boreholes during Apollo 15 and Apollo 17 missions. Basing on the Apollos data and using equation (6) it is possible to recalculate the Earth thermal flux. The resulting values are 43 and 65 TW. It is believed that these data do not contradict to LPI measurements because in that Apollo missions landing places the thermal fluxes should be significantly less than the mean value. It is supported by the Moon pictures made by the infrared telescope installed on board of the NASA satellite Lunar Reconnaissance Orbiter in 1996 during the full lunar eclipse.

Finally, let's estimate the upper limit of the Earth thermal flux. There are certain places on the Moon surface which are never illuminated by the Sun. The places have always constant temperature. We can assume that only radiogenic internal heat determines their temperature. So, the energy flux emitted by the Moon surface unit can be estimated according to the Stephan-Boltzmann law. Then it is possible to calculate the total thermal flux of the Moon. The Earth thermal flux recalculated using (6) is 420 TW. The value is obtained taking into account the temperature of 40°K in places never illuminated by the Sun at the Moon's South Pole region. The value of 420 TW for the Earth thermal flux can be regarded as an upper limit. This upper limit shows that the ^{238}U, ^{232}Th and ^{40}K masses in the Earth presented in (4) are too large. Whereas the masses shown in (5) result in the Earth thermal flux of 304 TW. The last value is smaller than the upper limit.

4. Conclusion

1. The HE model is a convenient tool for analysis of events taking place on the Earth. We demonstrated in the framework of the HE model that many complicated phenomena could find explanations in a natural way basing on just one model. Those are the geoneutrino fluxes, temperature profiles of super deep boreholes and experimentally observed increase of the ocean temperature.

2. It was shown that the HE model introduces the large concentrations of ^{238}U, ^{232}Th and ^{40}K in the Earth and allows their existence in the Earth core in primordial amount with correction for the elements decay. The most prominent amount appeared to be for potassium in comparison with the Bulk Silicate Earth model prediction due to its small ionization potential.

3. An assumption was done that the modern value of the Earth thermal flux resulting from the temperature gradient measurements does not take into account significant amount of heat transferred by hot gases. The Hydride Earth model predicts production of gases at high depths. The existence of this kind of heat transfer mechanism, additional to thermal conductivity, allows understanding of high temperature existing at big depths in deep boreholes on continents and in oceans.

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5. References

[1] *Agostini M. et al. (Borexino Collab.)* Spectroscopy of geoneutrinos from 2056 days of Borexino data // Phys. Rev.D., 92, 031101, 2015.

[2] *Gando A. et al. (KamLAND Collab.)* Reactor on-off antineutrino measurement with KamLAND // Phys. Rev.D. 2013. V. 88. P. 033001; arXiv:1303.4667v2 [hep-ex].

[3] *Bellini G., Ludhova L., Ianni A., Mantovani F., McDonough W.F.* Geo-neutrinos // Progress in Particle and Nuclear Physics, 73, 1, 2013.

[4] *Yu Huang, Viacheslav Chubakov, Fabio Mantovani, Roberta L. Rudnick, William F. McDonough* A reference Earth model for the heat producing elements and associated geoneutrino flux. arXiv:1301.0365v2 [physics.geo-ph]

[5] *Larin,V. N.* Hydridic Earth: the New Geology of Our Primordially Hydrogen-Rich Planet ed. C. Warren Hunt. Calgary, Alberta, Canada: Polar Publishing, 1993.

[6] *Herve Toulhoat, Valerie Beaumont, Viacheslav Zgonnik, Nikolay Larin, Vladimir N. Larin.* Chemical Differentiation of Planets: A Core Issue. arXiv:1208.2909 [astro-ph.EP].

[7] *Bezrukov L.* Geoneutrino and Hydridic Earth Model. Version 2. Preprint INR 1378/2014. M., 2014. 12 p; arXiv:1308.4163[astro-ph.EP].

[8] *David R. Lide (ed).* CRC Handbook of Chemistry and Physics, 84th Edition, Section 10, Atomic, Molecular and Optical Physics; Ionization Potentials of Atoms and Atomic Ions Boca Raton, Florida: CRC Press, 2003.

[9] *L. B. Bezrukov, A. S. Kurlovich, B. K. Lubsandorzhiev, V. P. Morgalyuk, V. V. Sinev and V. P. Zavarzina* On geoneutrino // EPJ Web of Conference, QUARKS-2016. 2016. V. 125. 02004.

[10] *V. V. Sinev, L. B. Bezrukov, E. A. Litvinovich, I. N.Machulin, M.D. Skorokhvatov, S. V. Sukhotin* Looking for antineutrino flux from ^{40}K with large liquid scintillator detector // EPAN Letters, 46, 339, 2015; arXiv:1405.3140 [hep-ex].

[11] Cola super deep hole. Scientific results and research experience // Ed. board: P. A. Brodsky, D. M. Guberman, V. I. Kazansky, O. L. Kuznetsov, V. B. Mazur, N. V. Militenko, F. P. Mitrofanov, A. F. Morozov, L. A. Pevzner, B. N. Chachaev, Yu. N. Yakovlev, Moscow: MF "Technoneftegaz", 1998.

[12] *J. Hansen, M. Sato, P. Kharecha, and K. von Schuckmann*. Earth's energy imbalance // Atmos. Chem. Phys. 2011. V. 11, P. 13421-13449.

[13] *Krotikov V.D., Troitskyi V.S.* Radio emission and nature of the Moon // Soviet Phys. Uspekhi. 1964. V. 6. P. 841-871.

Search for astrophysical neutrino sources at the Baksan Underground Scintillation Telescope

M.M. Boliev[1], A.V. Butkevich[1], I.M. Dzaparova[1,2], M.M. Kochkarov[1], R.V. Novoseltseva[1], V.B. Petkov[1,2] P.S. Striganov[1],V.I. Volchenko[1] and A.F. Yanin[1]

[1] Institute for Nuclear Research of RAS, Moscow, Russia; boliev2005@yandex.ru

[2] Institute of Astronomy of RAS, Moscow, Russia

Abstract Baksan Underground Scintillation Telescope is an underground detector located at the Northern Caucasus (Russia). The BUST can detect an astrophysical flux of neutrinos from Galactic sources as an excess of cosmic ray muon neutrinos arriving from the source direction. The search performed using 38 years (live time = 31.05) of the BUST dataset to look for a statistically significant excess of events arriving within a solid angle. No significant excess of events produced by astrophysical sources is found. Since the number of detected events is compatible with the number of expected background events upper limit on the muon neutrino flux is determined.

Keywords: Cosmic Rays, Neutrino, Astrophysics, Galaxies, Local Sources

1. Experimental Data

The Baksan Underground Scintillation Telescope (BUST) [l] is located in the underground laboratory at the effective depth of 850m.w.e. The detector itself is a parallelepiped 16.7 x 16.7 x ll m^3, all sides of which are entirely covered by liquid scintillator counters of the standard type (0.7m x 0.7m x 0.3m). There are also two additional horizontal layers inside, at distances of 3.6 and 7.2 meters from the bottom. Thus the detector consists of four horizontal and four vertical planes, each separated from the other by m160g/cm2 of absorber. The total number of the detectors is 3180. Every counter is viewed with one PMT (the 15 cm diameter photocathode). The construction of BUST allows one to identify tracks of muons crossing the telescope. Separation of arrival directions between up and down hemispheres is made by time-of-flight (TOF) method with time resolution 5 ns [2]. The angular resolution of the BUST for reconstructed events is about 1.6°.The detection of upward-going muons is performed by means of the time-of-flight method. In first period (1978 – 2000) two hardware triggers are used in order to reject downward-going atmospheric muons. Trigger I covers the zenith angle range 95° — 180°, while trigger II selects horizontal muons in the range 80° — 100°, for more details see ref [3,4]. Since 2000 year no use hardware triggers for select neutrino events.

The data used for this analysis have been collected from December of 1978 until June of 2017, for a total of 31.05 live-years. It was found that 1635 events survived these cuts.