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## EXTRAGALACTIC ASTRONOMY AND COSMOLOGY

# Heat Flow of the Earth and Resonant Capture of Solar $^{57}$Fe Axions[1]

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**Abstract**—In a very conservative approach, supposing that all heat flow of the Earth is exclusively due to resonant capture inside the Earth of axions emitted by $^{57}$Fe nuclei on Sun, we obtain limit on the mass of hadronic axion: $m_a < 1.8$ keV. Taking into account release of heat from decays of $^{40}$K, $^{232}$Th, $^{238}$U inside the Earth, this estimation could be improved to the value: $m_a < 1.6$ keV. Both the values are less restrictive than limits set in devoted experiments to search for $^{57}$Fe axions ($m_a < 216$–745 eV), but are much better than limits obtained in experiments with $^{83}$Kr ($m_a < 5.5$ keV) and $^{7}$Li ($m_a < 13.9$–32 keV).

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## INTRODUCTION

The general form of the Hamiltonian of quantum chromodynamics (QCD) contains a term that violates the CP symmetry in the strong interaction [10, 24]. However, this violation is not observed experimentally. For example, only upper (and very strict) limit is measured for the neutron electric dipole moment, which is contributed by the CP violating term: $d < 2.9 \times 10^{-26}$ $e$ cm [1]. This contradiction is known as the strong CP problem of QCD. One of the most simple and elegant solutions of this contradiction was proposed by Peccei and Quinn in 1977 [33, 34] by introducing a new global symmetry. The spontaneous violation of the PQ symmetry at the energy scale $f_a$ totally suppresses the CP violating term in the QCD Hamiltonian. Weinberg [43] and Wilczek [44] have independently shown that this model leads to existence of axion—a new pseudo-scalar neutral particle. The mass of axion is connected with the scale of the PQ symmetry violation: $m_a$ (eV) $\approx 6 \times 10^6/f_a$ (GeV). The interaction of axion with different components of usual matter is described by different effective coupling constants: $g_{a\gamma}$ (interaction with photons), $g_{ae}$ (electrons), $g_{aN}$ (nucleons), which are also inversely proportional to $f_a$ and those values are unknown (additionally, one should note that relations of $g_{a\gamma}$, $g_{ae}$, $g_{aN}$ with $f_a$ are model dependent).

In the first works, the energy of the PQ symmetry violation was considered to be close to the scale of the electro-weak symmetry violation and, therefore, the axion mass is ~100 keV. But this value of the axion mass was soon excluded by experiments with radioactive sources, reactors and accelerators (see reviews [1, 3, 10, 23, 24, 29, 37, 38] and references therein). Then the standard axion (known as PQWW by names of authors) was substituted by other models which allow much bigger values of $f_a$ up to the Planck mass of $10^{19}$ GeV: the hadronic axion model (KSVZ) [22, 39] and the model of the GUT axion (DFSZ) [13, 45]. The axion mass and the coupling constants $g_{a\gamma}$, $g_{ae}$, $g_{aN}$, which are inversely proportional to $f_a$, can have very small values ($m_a$ down to $10^{-12}$ eV) in these models, and these axions are sometimes named as "invisible". It should be noted that, besides the solution of the strong CP problem, axion is one of the best candidates on the role of the dark matter particles. The dark matter, in accordance with the contemporary conceptions, constitutes ≈23% of all the matter of the Universe (other components are the ordinary baryonic matter ≈4% and the so called dark energy ≈73%) [3, 7, 23, 29, 37, 38, 40].

If axions exist, the Sun can be an intensive source of them. They can be born (1) in the interaction of thermal gamma quanta with fluctuating electromagnetic fields within the Sun due to the Primakoff effect and (2) in nuclear magnetic transitions in nuclides present in the Sun.

[1] The article was translated by the authors.

The first effect generates the continuous spectrum of axions with energy up to ~20 keV and the mean value of 4.2 keV [41]. The total flux of the thermal axions depends on the coupling constant $g_{a\gamma}$ as $\varphi = (g_{a\gamma} \times 10^{10}\,\mathrm{GeV})^2 \times 3.5 \times 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The relation of the axion mass $m_a$ with $g_{a\gamma}$ is model dependent; for example, this flux is equal (in terms of $m_a$) to $\varphi = (m_a/1\,\mathrm{eV})^2 \times 7.4 \times 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the model with GUT axion, whereas other models can possess a deeply suppressed axion-photon coupling constant [41].

In the second effect, de-excitation of excited nuclear levels in magnetic (M1) transitions can produce quasi-monoenergetic axions instead of gamma quanta, due to axion-nucleon coupling $g_{aN}$. The total energy of axions is equal to the energy of gamma quanta. These levels can be excited by thermal movement of nuclei (the temperature of the solar core is equal to ~1.3 keV, and, therefore, only low-lying levels, like 14.4 keV level of $^{57}$Fe or 9.4 keV level of $^{83}$Kr, arc excited effectively). Other possibility of populating the excited levels is the nuclear reactions in the Sun (for example, the 477.6 keV level of $^{7}$Li is populated in the main *pp* cycle).

In spite of the theoretical attractivity of axions, any direct experimental evidences of their existence are still absent. Indirect astrophysical and cosmological arguments give advantage to the axion mass in the range $10^{-6}$–$10^{-2}$ eV or about 10 eV [1, 3, 23, 29, 37, 38]. The laboratory searches for axion are based on several possible mechanisms of axion interactions with the ordinary matter [3, 23, 29, 37, 38]: (1) the inverse Primakoff effect, i.e. conversion of axion to photon in laboratory magnetic field (an example of such the experiment is CAST [46]) or in a crystal detector (for example, NaI [6]); (2) the Compton conversion of axion to photon (analogue of the Compton effect) $a + e \longrightarrow \gamma + e$ [5]; (3) the decay of axion to two photons $a \longrightarrow \gamma\gamma$ [5]; (4) the axioelectric effect of interaction with an atom $a + (A, Z) \longrightarrow e + (A, Z)$ (analogue of photoeffect) [5]: (5) the resonant absorption of axions emitted in nuclear M1 transitions in a radioactive source, a nuclear reactor or the Sun by the analogue nuclei in a target (see details below). It should be noted that these mechanisms are based on different kinds of interactions of axion with matter, they are sensitive to different coupling constants ($g_{a\gamma}$, $g_{ae}$, $g_{aN}$), and the limits on the values of the constants and on the axion mass are model dependent. Thus, diverse experiments are mutually complementary. While the most of experiments concern the axion-photon coupling constant $g_{a\gamma}$, only the mechanism (5) is related to the axion-nucleon constant $g_{aN}$ both in emission and in absorption of axion. This allows to exclude uncertainty related to the values of $g_{a\gamma}$ and $g_{ae}$.

In the next chapters, we will discuss the last mechanism in more detail and will set the restriction on the axion mass in conservative assumption that all the heat generation within the Earth is caused exclusively by the resonant absorption of the solar axions. The possible contribution of radioactive decays of $^{40}$K and of the families of U and Th to the heat flow will also be taken into account.

## THE HEAT GENERATION IN THE EARTH BY THE RESONANT CAPTURE OF SOLAR AXIONS

As mentioned above, axions can be emitted instead of gamma quanta in nuclear magnetic transitions (M1) during de-excitation of excited levels of nuclei present in the Sun. The corresponding axion flux depends on abundance of such nuclei, on radial dependence of the abundance (because of radial dependence of temperature which is important for thermal excitation of the levels), on the energy of the level (the thermal movement populates low-lying levels more effectively), on the mean life of the level and on the probability of axion emission instead of gamma quantum in the nuclear transition. The last value depends on the axion-nucleon coupling constant $g_{aN}$ and on the corresponding nuclear matrix elements. The calculations should also take into account the probability of absorption of the emitted axion in the solar matter.

The expected axion fluxes from thermally excited first levels of $^{23}$Na ($E_{\mathrm{exc}}$ = 440.0 keV), $^{55}$Mn ($E_{\mathrm{exc}}$ = 126.0 keV), $^{57}$Fe ($E_{\mathrm{exc}}$ = 14.4 keV) were calculated in [17]. The axion flux from $^{57}$Fe is maximal because of the lowest exciting energy: $\varphi_{57} = 8.5 \times 10^7\,(m_a/1\,\mathrm{eV})^2\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [28]. The fluxes from $^{23}$Na and $^{55}$Mn are lower by orders of magnitude; they are suppressed by the Boltzmann factor $\exp(-E_{\mathrm{exc}}/kT)$, where $kT \approx 1.3$ keV in the solar center, while the abundances of all 3 nuclides are of the same order. The new principle of search for such axions was proposed in [31]: if resonant conditions are fulfilled, the solar axion can be captured by a respective nucleus (for example, $^{57}$Fe) on the Earth. The particles emitted in the subsequent de-excitation of this nucleus (gamma quanta, X rays, conversion electrons) can be registered by a suitable detector which is placed about the $^{57}$Fe target (or contains $^{57}$Fe nuclei in the sensitive volume). The characteristic peak with energy of 14.4 keV would be observed in the spectrum of the detector in these conditions.

In the first experiment dedicated to search for the solar $^{57}$Fe axions [25], the iron target (containing 2.1% of $^{57}$Fe) and Si(Li) detector were used. The 14.4 keV peak was not observed, that gave only the upper limit on the axion mass: $m_a < 745$ eV. This restriction was recently improved to values of $m_a < 360$ eV [12] and $m_a < 216$ eV [32].

Axions supposedly emitted by thermally excited solar $^{83}$Kr nuclei ($E_{exc}$ = 9.4 keV) were searched for in the experiment [16], where gaseous proportional counter filled by Kr (11.5% of $^{83}$Kr) was used. The characteristic peak was not observed, and the respective limit on the axion mass was $m_a$ < 5.5 keV.

M1 transitions from the first excited level of $^7$Li ($E_{exc}$ = 477.6 keV) can also be a source of quasi-monoenergetic axions [26]. This level is populated in the main *pp* chain of nuclear reactions in the Sun (which is directly connected to the solar luminosity), when a $^7$Be nucleus produced by reaction $^3\text{He} + \alpha \longrightarrow {}^7\text{Be} + \gamma$ decays into $^7$Li. In this decay, the 477.6 keV level is populated with probability of 10.5% [15]. In the first experiment [26] on search for such axions, a lithium target of 60 g mass and a HPGe detector were used during 111 days of measurements; the sought effect was not observed, and only limit on the axion mass $m_a$ < 32 keV was set. The two following experiments have improved this limit to $m_a$ < 16 keV [11] and $m_a$ < 13.9 keV [4].

The nuclei of $^7$Li, $^{23}$Na, $^{55}$Mn, $^{57}$Fe, $^{83}$Kr, etc. can be excited by solar axions not only in specially selected targets but everywhere. In particular, de-excitation of the resonantly excited levels of these nuclei can contribute to the total heat flow from our planet's depths. Let us estimate the axion mass in a very conservative assumption that all the Earth's thermal flux is caused by resonant absorption of solar axions within the Earth.

The directly measured heat flow from both oceanic bottom areas and continents leads to estimation of global power to the value of $(31 \pm 1) \times 10^{12}$ W [20]. However, it is widely accepted that this value is an underestimate due to hydrothermal redistribution of heat flow in oceanic regions and model values are used instead: $(44 \pm 1) \times 10^{12}$ W [35] or $(46 \pm 3) \times 10^{12}$ W [27]. It is considered that about half of this heat is being created by radioactive decays of $^{40}$K and nuclei in the chains of $^{238}$U and $^{232}$Th. The distribution of these isotopes over the Earth's crust, mantle and core is not exactly known, but it is accepted that K, U and Th tend to concentrate in the crust. The Earth's internal composition (and the distribution of radioactive nuclei) can be investigated by massive (mass of 1 kt) detectors of antineutrinos emitted in nuclear decays within the Earth (the so-called geo-neutrinos). It is one of the priority tasks of the modern physics [14]. In particular, the Herndon's hypothesis on the nuclear reactor existing in the Earth's center [18, 19, 21] can be checked. The heat flow from decays of U/Th/K is estimated as $20 \times 10^{12}$ W (see [14] and references therein); however, there exist estimations as high as $(33–43) \times 10^{12}$ W [2].

According to the contemporary conceptions [2], the Earth consists of the crust (0–35 km), the upper mantle (35–660 km), the lower mantle (660–2900 km), the outer core (2900–5150 km), and the inner core (5150–6370 km). The mass of the mantle is near 68% of the whole Earth's mass, it contains 6.26% of Fe. The core (~32% of the Earth's mass) includes mainly iron. It is considered that the Earth was formed from the primitive matter which had the composition of CI chondrites. Taking this model, the authors of [30] calculated that the core contains 78.0–87.5% of Fe, and all the Earth—29.6–32.7% of Fe. The chondritic model is criticized recently [9, 20, 42], but the proposed corrections to this model do not change significantly the total content of iron in the Earth.

The natural abundance of $^{57}$Fe was measured in samples of different origin (crust minerals, magma, different types of meteorites); the differences are small [36], and the recommended value of $\delta = 2.119\%$ [8] can be used for the $^{57}$Fe abundance. Taking the Earth's mass of $5.97 \times 10^{27}$ g [1], the mass of $^{57}$Fe in the Earth can be estimated as $(3.7–4.1) \times 10^{25}$ g that corresponds to the number of nuclei $N_{57} = (4.0–4.4) \times 10^{47}$.

The number of resonant captures of solar axions in a target with $N_{57}$ nuclei of $^{57}$Fe per 1 s is equal [12]:

$$R = 4.5 \times 10^{-33} N_{57} (m_a / 1\ \text{eV})^4. \tag{1}$$

The energy of 14.4 keV is released after every capture. This energy is totally absorbed in the Earth's body. Taking conservatively the lower possible value of the number of $^{57}$Fe nuclei $N_{57} = 4.0 \times 10^{47}$, and the highest possible estimation for the Earth's heat flow [27] $46 \times 10^{12}$ W = $2.9 \times 10^{32}$ eV/s, we equalize the last quantity to the power generated by axion captures $2.6 \times 10^{19}$ $(m_a/1\ \text{eV})^4$ eV/s and obtain the upper limit

$$m_a = 1.8\ \text{keV}. \tag{2}$$

The real value of $m_a$ cannot be greater than this value. If one takes into account that about half of the heat flow—$20 \times 10^{12}$ W [14] or even $(33–43) \times 10^{12}$ W [2]—can be generated by radioactive decays of $^{40}$K, $^{232}$Th, $^{238}$U within the Earth, the estimation (2) can be improved. Subtracting conservatively the lowest of possible rates of radioactive energy generation ($20 \times 10^{12}$ W) from the maximal total Earth's heat flow ($46 \times 10^{12}$ W) and attributing the difference to the heat generation from axion captures, we obtain the following upper limit on the axion mass:

$$m_a = 1.6\ \text{keV}. \tag{3}$$

Both of the restrictions are few times worse than the limits obtained in direct experiments searched for solar $^{57}$Fe axions: 216–745 eV [12, 25, 32]. However, they are much better than the limits obtained in the experiments with $^{83}$Kr ($m_a$ < 5.5 keV [16]) and $^{7}$Li ($m_a$ < 13.9–32 keV [5, 11, 25]).

## CONCLUSIONS

In a very conservative approach, supposing that all the heat flow of the Earth is exclusively due to resonant capture of axions, emitted by $^{57}$Fe nuclei on Sun, we get the limit on the axion mass: $m_a$ < 1.8 keV. Taking into account the heat generated in decays of $^{40}$K, $^{232}$Th, $^{238}$U within the Earth, this limit can be improved to $m_a$ < 1.6 keV. Both of the values are worse than the limits $m_a$ < 216–745 eV obtained in direct laboratory searches for $^{57}$Fe solar axions but are much better than the limits obtained in the experiments with $^{83}$Kr ($m_a$ < 5.5 keV [16]) and $^{7}$Li ($m_a$ < 13.9–32 keV [5, 11, 25]). Since the rates of both emission and resonant capture of axion are governed by the axion-nucleon coupling constant $g_{aN}$, the obtained limits do not depend on uncertainties in values of the axion-photon ($g_{a\gamma}$) and axion-electron ($g_{ae}$) coupling constants.

We used the fact that the flux of monoenergetic solar $^{57}$Fe axions should be greater than the fluxes of $^{7}$Li, $^{23}$Na, $^{55}$Mn and $^{83}$Kr axions, as well as that the approximately third part of the Earth mass is iron. In the following, we plan to improve the obtained limit by taking into account the contributions from other possible mechanisms of axion interactions with the Earth's matter: the axioelectric effect, the Compton axion-photon conversion, the axion decay to two photons, etc.

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