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A1_7 The Neutrino Problem

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Abstract

This report examines the premise from the movie "2012" (2009) that solar neutrinos start interacting with the core of the Earth, causing it to melt. A lower energy limit required for this interaction is found to be $9.55 \cdot 10^{4}\text{GeV}$ and it is shown that the source of such energetic neutrinos is unlikely to be from within the solar system.

Introduction

Neutrinos are subatomic elementary particles with no charge and a non-zero mass. As they only interact via the weak interaction, regular matter is rarely affected by them [1]. In the movie "2012", solar neutrinos start interacting with the regular matter in the core of the Earth, melt it and eventually destabilize the crust [2]. In this paper we check whether the initial idea of neutrinos melting the Earth's core is feasible with the currently known data about solar neutrinos.

Discussion

Neutrinos are generated in the Sun primarily via the pp chain reaction, which converts four protons and two electrons into a ${}^{4}_{2}\text{He}$ nucleus and two electron neutrinos:

$$4\text{p} + 2\text{e}^{-} \rightarrow {}^{4}_{2}\text{He} + 2\nu_{\text{e}} + \text{Q}, \qquad (1)$$

where $Q = 26.73\,\text{MeV}$ is the total energy released. This energy is mostly released as photons or as the kinetic energy of the electron neutrinos. The kinetic energies of the vast majority of neutrinos fall in the range of $0 - 15\,\text{MeV}$ [3]. The neutrino weak interaction cross-section, σ, can be approximated as [4]

$$\sigma \approx G_{\text{F}}EM = 10^{-38}\text{cm}^2\,\frac{EM}{\text{GeV}^2}, \qquad (2)$$

where $G_{\text{F}} = 1.166 \cdot 10^{-5}\,\text{GeV}^{-2}$ is the Fermi constant [5], E is the neutrino energy, and M is the mass of the target particle. The free path length, i.e. the distance over which a neutrino will interact, can be calculated as

$$l = \frac{1}{N\sigma} = \frac{1}{NG_{\text{F}}EM} = \frac{10^{38}\,\text{cm}}{(N\,\text{cm}^3)\left(\frac{EM}{\text{GeV}^2\text{c}^{-2}}\right)}, \qquad (3)$$

where N is the target particle number density. (The RHS of Eq. 3 requires N in units of cm^{-3}, E in GeV and M in GeVc^{-2}). The inner core of Earth is assumed to be a solid sphere of iron with a radius of $R = 1250\,\text{km}$, constant temperature $T = 5500\,\text{K}$, and a density of $\rho = 15\,\text{g/cm}^3$ [6]. The number density then is:

$$N = \frac{\rho N_{\text{A}}}{M_{\text{Fe}}} = 1.62 \cdot 10^{23}\,\text{cm}^{-3}, \qquad (4)$$

where ρ is the density of the core, N_{A} is Avogadro's constant, and $M_{\text{Fe}} = 55.8\,\text{g mol}^{-1}$ is the molar mass of iron. Assuming a single average incoming solar neutrino of $1\,\text{MeV}$ energy and the target particle to be an iron atom of mass $M = 9.27 \cdot 10^{-23}\,\text{g} = 52.02\,\text{GeVc}^{-2}$, the mean free path length through the core of the Earth is

$$l = 1.2 \cdot 10^{16}\,\text{cm} = 0.012\,\text{ly}. \quad (5)$$

It is clearly seen that solar neutrinos have a very long mean free path; even through solid, dense iron; and as such, with no changed conditions, the premise of “2012” cannot be correct.

Alternatively, we could consider a non-solar source of neutrinos, which could potentially have high enough energies to interact with the core of the Earth, e.g. a supernova. Then the lower energy limit for the neutrinos can be found if we assume they interact within a mean free path length of $R = 1250\ \mathrm{km}$:

$$E = \frac{1}{NG_{\mathrm{F}}RM} = 9.55 \cdot 10^4 \mathrm{GeV}. (6)$$

Now, assuming all the neutrinos incident on the Earth have this energy, interact only with the core of the Earth, and upon interaction transfer all their kinetic energy to heat; the time required for the solid inner core to melt can be found. To further simplify the calculation, it is assumed that the core of the Earth is at a constant pressure of $P = 364\ \mathrm{GPa}$. The melting point at this immense pressure is not very well known, but was modelled to be at $T = 6630\ \mathrm{K}$ [7], and the specific heat capacity $c = 4600\ \mathrm{J\ kg^{-1}\ K^{-1}}$ [8] stays constant. The amount of energy required to melt is

$$Q = \frac{4}{3}\rho\pi R^3 c\Delta T, \qquad (7)$$

and was found to be $Q = 6.4 \cdot 10^{29}\ \mathrm{J}$. As the energy of a single energetic neutrino was calculated in Eq. 6 to be $15.3\ \mu\mathrm{J}$, the total number of interactions required to transfer this energy is $A = 4.18 \cdot 10^{34}$.

Conclusion

It is clear that solar neutrinos cannot be the main cause of melting the core of the Earth, as common fusion reactions do not produce anywhere enough energy to make GeV neutrinos. The current measured flux of cosmic neutrinos on Earth is $3 \cdot 10^{12}\ \mathrm{cm^{-2}\ s^{-1}}$ [9], so for the premise to be true, an extreme event is required to produce both the required flux and provide enough kinetic energy to the neutrinos. Further analysis could determine if such events are possible, but even if they are, they are likely to be accompanied by other highly energetic forms of radiation, which would eliminate all life forms long before the structure of the Earth is damaged via neutrino interaction.

References

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