Highlights

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Abstract

The concept of putting a neutrino detector in close orbit of the sun has been unexplored until very recently. The primary scientific return is to vastly enhance our understanding of the solar interior, which is a major NASA goal. Preliminary calculations show that such a spacecraft, if properly shielded, can operate in space environments while taking data from neutrino interactions. These interactions can be distinguished from random background rates of solar electromagnetic emissions, galactic charged cosmic-rays, and gamma-rays by using a double pulsed signature. Early simulations of this project have shown this veto schema to be successful in eliminating background and identifying the neutrino interaction signal in upwards of 75% of gamma ray

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interactions and nearly 100% of other interactions. Hence, we propose a new instrument to explore and study our sun. Due to inverse square scaling, this instrument has the potential to outperform earth-based experiments in several domains such as making measurements not accessible from the earth’s orbit.

Keywords: neutrino, gallium, double-pulse, solar, scintillating crystal

1. Introduction

Since neutrinos interact only weakly they are hard to detect; nevertheless, within the last ten years neutrino detectors on earth have started to reliably detect neutrinos from the fusion reactions in the interior of the sun and scientists have started to use this information to investigate the sun’s nuclear furnace. These neutrino detectors are normally very large and deep underground. They are large because they need as much mass as possible to capture more neutrinos, and they are underground to reduce background rates. If a neutrino detector could operate in space, what advantages would it have to perform unique science? Clearly to just take a neutrino detector into space may not bring any new science unless the possibility for dramatically enhancing the neutrino flux was associated with this endeavor, but it could also be of interest if it can dramatically reduce solar neutrino backgrounds to see other processes such as dark matter or galactic neutrinos currently hidden by a large solar neutrino presence at the earth.

We propose three distinct possibilities for science using the Neutrino Solar Observatory (νSOL):

1. Going closer to the sun, see Table 1 the $1/r^2$ neutrino flux would provide 1,000x more neutrino rates at seven solar radii distance where the current NASA Parker Solar Probe operates and 10,000x more neutrino rate at three solar radii where some NASA scientists think it is possible to go [1]. Here new science would be a larger statistical observation of solar neutrino emission, the study of the size of the fusion emission region, and particle physics looking for the transition from coherent to de-coherent neutrino oscillations. The sun’s gravitational well could trap dark matter in its core and this would displace the solar fusion region and would be a way to search for dark matter’s presence without direct detection [1].
2. Because the neutrino has a non-zero mass, which we know from the existence of neutrino oscillations, the sun bends space to create a gravitational focus, but for neutrinos this gravitational focus would be very close to us at 20 to 40 AU: a distance easily reachable with current technology, unlike the gravitational focus for light which is 450 to 750 AU away [2]. This solar neutrino focus could be a testing ground for gravitational lens ideas. The galactic core is 27,000 light years away from us and is about two times larger than the moon when viewed from earth and is the 2nd largest neutrino source in the sky after the sun [3, 4, 5]. The galactic core not only has many neutrino-producing stars, but also 10,000 neutron stars and black holes in the central cubic parsec of the core. Matter falling into these objects is crushed, producing neutrons and isotropically emitted neutrinos of higher energy than solar fusion neutrinos. A detector at the solar neutrino focus would permit imaging of the galactic core and just finding the neutrino gravitational focus of the sun would be a new way to measure the neutrino mass.

3. Any neutrino-detecting space probe could take advantage of a flight towards the sun to observe the shape of the solar neutrino changes due solely to the distance from a non-point source of solar neutrinos inside the sun, while when traveling away from the sun, deviations from the expected $1/r^2$ curve are an indication of the direct observation of dark matter or galactic neutrinos [1].

Although operating a neutrino detector in space will be challenging, we believe we have found a way to do just so. Our technique would permit operation and detection in space, would be a major advance for astrophysics and heliophysics, and would allow for new ways to make elementary particle physics fundamental measurements, all of great importance.

2. Neutrino Physics in Space

2.1. Disadvantages

The most obvious disadvantage of a space-based detector is the harsh environment of space. Most neutrino detectors have the luxury of being built deep underground in order to eliminate most cosmic backgrounds. A space-based detector will have to contend with the full flux of energetic cosmic gamma rays, electrons, protons, and heavier nuclei. The first level of shielding for these events comes from the outermost iron shell.
### Distance from Sun vs. Flux relative to Earth

| Distance from Sun | Flux relative to Earth |
|-------------------|------------------------|
| 696342 km ($R_\odot$) | 46200                  |
| 1500000 km ($\sim 3R_\odot$) | 10000                  |
| 4700000 km ($\sim 7R_\odot$) | 1000                   |
| 15000000 km | 100                    |
| 47434000 km | 10                     |
| Mercury | 6.4                    |
| Venus | 1.9                     |
| Earth | 1                      |
| Mars | 0.4                    |
| Asteroid Belt | 0.1                    |
| Jupiter | 0.037                  |
| Saturn | 0.011                  |
| Uranus | 0.0027                 |
| Neptune | 0.00111               |
| Pluto | 0.00064                |
| KSP | 0.0002                 |
| Voyager 1 (2015) | 0.00006                |

Table 1: Intensity of solar neutrinos at various distances from the sun.
The first significant source of background events in space is the gamma ray/x-ray background. Our passive shield can stop the energy of gamma rays up to 600 keV with better than $2 \cdot 10^{-4}$ attenuation \[6\]. This should be more than sufficient to shield against the gamma ray background. The total gamma background can be seen in Figure 1 from 0.5 keV to 2.5 GeV. The sufficiently energetic gammas, in the energy range of 500 keV and above, create a background of approximately $130 \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ \[7\]. Our electronics are being designed so that they are sufficient to deal with this noise on the order of 500 Hz.

Figure 1: Cosmic gamma ray spectrum vs photon energy. Fermi gamma-ray data extends to 100 GeV, but the contribution to the total rate is small \[7\].

There are two major sources of electrons in terms of space conditions. The solar wind electrons have a characteristic temperature of 12 eV at the earth \[8\]. This temperature will increase, using the worst case of Boldyrev, Forest, and Egedal, to a maximum temperature of 130 eV \[9\]. These are both well below energies at which any significant fraction of electrons might penetrate the satellite’s shielding. The second source is the cosmic background electrons. These background electrons, Figure 2, have been measured with a total rate of approximately $50 \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ on the MeV-TeV regime. The iron shield will moderate electrons and, in the continuously slowing down approximation (CSDA), the shielding will be 100% effective at energies up to 15 MeV \[10\]. At energies beyond this, there will begin to be penetration, and we will rely on active veto rejection techniques.

Similar to electrons, the solar wind and cosmic background are the primary sources of positively charged particles. The solar wind protons have a
Figure 2: Cosmic electron differential flux vs electron kinetic energy. [11]
normative temperature of 18 eV, and the maximum temperature measurement of the DSCOVR solar wind warning probe in the earth-sun L1 point has measured maximum proton temperatures of approximately 86 eV. These energies are well below the MeV scales of the passive shielding [12]. The total cosmic flux of protons and heavier nuclei is well measured, and the total flux is on the order of 3000 m$^{-2}$ sr$^{-1}$ s$^{-1}$ from 100 MeV and up [13]. In the CSDA, the shield will be able to stop protons of energy up to 80 MeV, and it will be able to stop alpha particles up to 300 MeV.

2.2. Advantages

In the introduction, we touched briefly on one advantage of approaching the sun, and here expand on the scope of what it means to go close to the sun. The most obvious advantage is the previously mentioned inverse square scaling. Due to the weakly interacting nature of the neutrino, we can expect the flux of neutrinos to fall off as an inverse square of the distance from which they were generated.

The dramatically increased flux from the inverse square scaling allows for a modestly sized detector, on the order of one hundred kilograms of
active volume. For a $3R_\odot$ science mission, this would be the flux-equivalent of a 1 kTon solid scintillating crystal detector, which is comparable to large earth-based experiments like the KamLAND, a 1 kTon mineral oil scintillator detector, and Super-K, a 50 kTon water Cherenkov detector [14, 15]. As we approach the sun, the flux spectrum will change slightly due to the shape of fusion in the core, but even on the scale of a $3R_\odot$ closest approach the variation in flux from the near peak of the fusion region to the far peak is on the order of 1%.

Figure 4: Flux of protons from 250-700 MeV by distance from sun [16].

It is worth noting that there does not seem to be much risk of increased backgrounds on approach to the sun. The Helios mission measured the proton flux down to 0.3 AU ($64.5R_\odot$), Figure 4 and found that the flux was unexpectedly flat. This phenomenon has been explained by the modulation of the high energy cosmic particles by the sun’s magnetic field and the acceleration of the low energy solar wind as it moves from the sun [17, 18].

Last, it is a straightforward feature of the geometry in orbit that the resolution of a detector increases with an inverse square scaling. Because of this, we get the same relative angular resolution scaling that the neutrino flux sees in Table 1. If our detector is only capable of one tenth the angular resolving power of detectors like Super Kamiokande, a relatively conservative mission to 20 solar radii would have significantly improved resolving power.
3. Gallium Double Pulsing

In section 2, we introduced the difficulty of measurement using traditional neutrino detection methods due to high background rates. To counteract this effect, we are designing a method of looking for electron-type neutrinos via a double pulse signal. The interaction of gallium with neutrinos has been of scientific interest since the early 1990's with the GALLEX experiment and the SAGE experiment [19, 20]. These experiments used radiochemical methods to determine the number of neutrino interactions which had taken place. These experiments were, and our experiment currently is, based on the specific interaction of a neutrino transmuting gallium into ionized germanium, and itself into an electron: \( \nu_e + \text{Ga} \rightarrow e^- + \text{Ge}^+ \).

It is important to note that the proposed method is not unique to any particular gallium-loading method, nor is it strictly necessary to use gallium. Several other elements could be used for solar neutrino measurements, such as indium. Our work has focused on gallium because it has the smallest \( Q = 235.7 \text{ keV} \) and largest cross section of other double-pulse candidates. Our current designs focus on the Gadolinium-Aluminum-Gallium Garnet (GAGG) scintillating crystal, but as we have mentioned, any gallium-loaded material could be used in this double-pulsing schema. In particular, Gallium III Oxide is an interesting scintillator in development because of its high gallium mass fraction in comparison with other crystals.

3.1. Gallium-Neutrino Interaction

We propose using a prompt scintillation method to determine when a neutrino interaction has occurred. The neutrino interaction will often leave the germanium atom without any excitation energy, but about half of the interactions will leave the germanium nucleus in an excited state, see Table 2. This motivates a method to look for an initial electron energy deposit followed by a gamma ray with characteristic timing. This double pulsing allows us to reject a large fraction of events which bypass our shielding. This allows the potential for favorable signal-to-background ratios even in high-background environments like those of space.

The two isotopes of gallium present two different possibilities for neutrino detection. The first isotope we’ll discuss is gallium 71. Gallium 71 is transmuted into germanium 71 during interactions with electron type neutrinos. When the neutrino is sufficiently energetic, this will release an electron alongside the final germanium nucleus. The mass difference between gallium
and germanium 71 is 235.7(18) keV, and when combined with the mass of the electron, this gives a bare threshold of 746.7(18) keV for the energy of a neutrino able to eject an electron at rest from the ground state of germanium 71 [21, 13]. The gallium ground state has spin -3/2, whereas the germanium ground, first, and second excited states have spins of -1/2, -5/2, and +9/2 respectively. The -5/2 spin state has a half-life of 70 ns, and the metastable spin +9/2 state has a half life of 20.2 ms. The most likely excited state of the germanium is the -5/2 state, followed by several higher energy levels. The +9/2 state should be very unlikely in comparison [22, 23].

Current designs use a highly-segmented detector of small GAGG crystals. The detector will use silicon photomultipliers (SiPM) to read out the energy deposited in each of the GAGG cells, and this segmentation allows for sophisticated particle identification algorithms like have been used in the NOvA experiment [24]. A highly segmented design has not yet been implemented in simulation, but the work done in particle identification by the NOvA experiments should allow our detector to identify particle type and direction for more effective vetoing. Further studies will determine the efficacy of such a design, and these studies will determine if a sufficiently powerful computer or sufficiently high-rate communication device can be included for this analysis.

| Reaction Products | Energy Threshold | Photon Energy | Half Life |
|-------------------|------------------|---------------|-----------|
| Ge$^{71}$F$^2$ + e$^-$ | 0.408 MeV | 0.175 MeV | 79 ns |
| Ge$^{69}$M$^1$ + e$^-$ | 2.313 MeV | 0.086 MeV | 5 µs |
| Ge$^{69}$M$^2$ + e$^-$ | 2.624 MeV | 0.397 MeV | 2.8 µs |

Table 2: Table of the possible reactions of neutrinos with gallium and their decay products.

3.2. Simulations

We have extensively simulated the double pulsing in a variety of scintillator candidates, and detector configurations. While the exact vetoing rate changes based on the the detector configuration, the double pulsing has allowed some configurations to approach vetoing rates of 100% for all particles except galactic gammas. Galactic gamma rays have been successfully vetoed in simuo at rates of 75%. Ongoing topological and timing studies are promising to push this vetoing rate in line with the other particles. These simulations have focused on the ability of the detector system to identify a
neutrino-related pulse or reject a galactic cosmic ray (GCR) event, and what additional pulses are generated when these occur.

Long-term, the ability to detect a neutrino double pulse amongst the various sources of noise is of interest, as is determining the rate of accidental double pulses due to background events themselves or background events and neutrino pulses. This will require the construction of a fast Monte Carlo, in which each step in time is accompanied by a decision to emit a neutrino event or a background event. This includes both primary particles and any secondary events like those from activation products.

Before the current design and the updated version of Geant4 were implemented, an initial fast Monte Carlo program was built and run successfully. A key component of a previous design was the implementation of a shielding strategy to try to increase the removal of unwanted pulses. This strategy included alternating layers of metal and plastic in addition to the outer shell and the polymer veto. The purpose of said layers was to produce enough charged particles to better generate a signal in the veto scintillator. The basic approach was largely successful in reducing the rate from low energy gamma rays and protons. However, the current design has removed those layers in order to address other constraints on overall mass and orbit of the spacecraft around the sun. As the design evolves, inclusion of additional shielding can be considered.

4. Summary

In summary, we propose a near-solar neutrino detector design using the well-studied transmutation of gallium into germanium. This detector will be able to take advantage of the inverse square scaling of the neutrino flux to be the mass-equivalent of a detector on the scale of kilotons while at closest solar approach. By flying in the space between the earth and the sun, such a detector will be capable of probing the distance scales between the earth’s diameter and 1 AU and probing off-axis solar neutrinos, which are impossible for earth-based experiments.

Such a detector must contend with high-rate cosmic ray backgrounds. We propose to solve this problem by looking for a double-pulsed gallium signal. This double pulsing allows for dramatically improved rejection rates compared to single coincidence rejection. Future work will continue to refine detector topological rejections. Our rejection rate in-simuo is already at 75%
for gamma rays with little topological or timing cutting, and nearly 100%
for other background particles in similar regimes.

5. Acknowledgements

We would like to thank Nasser Barghouty of NASA Headquarters for
helping Nick Solomey put together the initial idea for the νSOL project
during a NASA summer fellowship.

Funding: This work was supported by the NASA NIAC Program [grant
numbers 80NSSC18K0868, 80NSSC19M0971]; MSFC CAN [grant number
80MSFC18M0047]; Wichita State University MURPA; NASA EPSCoR PDG.

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