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Recent Solar neutrino Results from Super-Kamiokande

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Abstract. Super-Kamiokande (SK), a 50 kton water Cherenkov detector in Japan, is observing neutrinos and searching for proton decay and dark matter. The installation of new front-end electronics in 2008 marks the beginning of the 4th phase of SK (SK-IV). With the improvement of the water circulation system, calibration methods, reduction cuts, this phase achieved the lowest energy threshold thus far: 3.5 MeV kinetic energy. SK studies the effects of both the solar and terrestrial matter density on neutrino oscillations: a distortion of the solar neutrino energy spectrum would be caused by the edge of the Mikheyev-Smirnov-Wolfenstein resonance in the solar core, and terrestrial matter effects would induce a day/night solar neutrino flux asymmetry. SK observed solar neutrino interactions for more than 20 years. This long operation covers about ~ 2 solar activity cycles. An analysis about a possible correlation between solar neutrino flux and 11 year activity cycle will be presented.

1. Introduction

The solar neutrinos are produced by the nuclear fusion reaction, $4p \rightarrow \alpha + 2e^+ + 2\nu_e$, in the core of the Sun. Electron neutrinos (ν_e) produced in the Sun are so called *pp*, *pep*, ${}^7\text{Be}$, ${}^8\text{B}$ and *hep* neutrinos, whose fluxes had been predicted by the standard solar model [1]. Their energy distributes from ~ 0.1 MeV to ~ 20 MeV.

Solar neutrino flux measurements from Super-Kamiokande (SK) [2] and Sudbury Neutrino Observatory (SNO) [3] have provided direct evidence for solar neutrino flavor conversion. However, there is still no clear evidence that this solar neutrino flavor conversion is indeed due to neutrino oscillations and not caused by any other mechanism.

The current interesting physics motivation of the solar neutrino observation with the SK detector [4] is to search for the Mikheyev-Smirnov-Wolfenstein (MSW) effect [5, 6]. The MSW effect leads to a resonant conversion of the higher energy solar neutrinos within the Sun and results in an about 30% level of the survival probability above a few MeV, which is so called “Up-turn”. Since the energy spectrum reflects the survival probability of the electron neutrinos, the SK searches for the “Spectrum up-turn” by measuring the recoil electron energy spectrum. In addition, due to the matter effect in the interior of the Earth, the electron flavor neutrinos are regenerated. It is expected that the neutrino flux in night is larger than that in day by about a few % level depending on the neutrino oscillation parameters. In 2014, SK reported an indication of the terrestrial matter effects by about 2.7σ [7].



2. ^8B solar neutrino flux measurement

In 2016, the Super-Kamiokande collaboration released a paper about the solar neutrino analysis results using SK-IV 1,664 days data set [8]. In this proceedings, the updated results are presented using data taken until the end of March 2016 (SK-IV 2,365 days data set) for the flux measurement. The total livetime throughout the difference phases of SK (SK-I [2], SK-II [9] and SK-III [10]) are 5,200 days.

The SK detector observes solar neutrino via the elastic scattering between the solar neutrino and the electron in pure water. In the case of ν - e interaction, the direction of the recoil electron is highly correlated with the direction of the incident neutrino. Figure 1 shows the distribution of cosine between the reconstructed direction of observed recoil electrons and the direction of the Sun. Using 5,200 days data, more than 84,000 events are observed so far. Based on this data, the ^8B solar neutrino flux is determined to be $(2.355 \pm 0.033) \times 10^6$ /cm²/sec assuming a pure electron neutrino flavor content. The ratio between the SK's result and the SNO's result of the neutral current measurement [11] becomes 0.4486 ± 0.0062 .

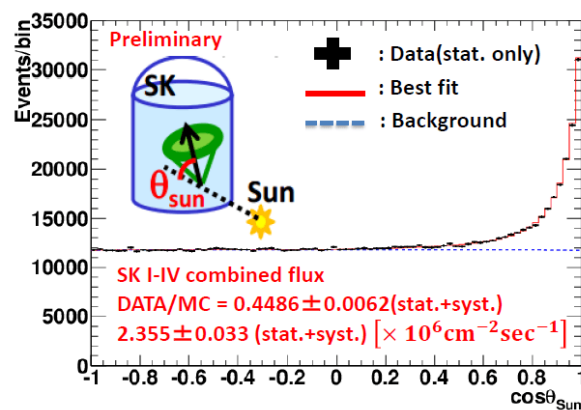


Figure 1. The solar angle distribution combining SK-I through SK-IV. The horizontal axis shows the cosine of the solar angle ($\cos \theta_{\text{Sun}}$) and the vertical axis shows the number of observed events. The black points show the observed data, the red (blue) histogram shows the best-fit result (background-shape).

3. Periodic signal search

3.1. Yearly flux measurement

Although the standard solar model predicts the production rate of solar neutrinos in the core of the Sun, it does not consider periodical activities of the Sun, for example, the rotation of the Sun, the variation of the sun spots on the surface of the Sun and the modulation of the solar magnetic fields. When a periodic signal of solar neutrinos is observed, this leads to an improvement of the standard solar model.

The solar activity cycle is the 11 years periodic change of sun spots releasing the magnetic flux at the surface of the Sun. The number of the sun spots strongly correlated with the solar activity cycle. If the neutrino has a magnetic moment, the magnetic field inside the Sun would cause precession of the neutrino spin [12, 13]. Therefore, checking the stability of the observed solar neutrino flux is important in order to understand the properties of the neutrino.

Since the SK has observed solar neutrinos for more than 20 years, this long term observation covers nearly 2 solar activity cycles. Figure 2 shows the SK yearly flux measured throughout the different phases of SK together with the corresponding sun spot number (Source: WDC-SILSO,

Royal Observatory of Belgium, Brussels [14]). Using the present data, the χ^2 is calculated with the total experimental uncertainties as $\chi^2 = 15.52/19$ d.o.f., which corresponds to a probability of 68.9%. The SK solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.

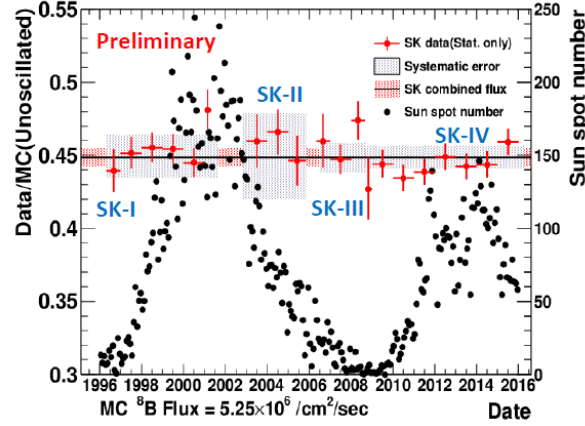


Figure 2. The result of the solar neutrino flux measurement from 1996 to 2015. The red points shows the yearly flux measured by SK (statistical error only), the gray bands shows the systematic uncertainties for each SK phase, the black-horizontal line shows the combined measured flux with the uncertainty drawn by the red band and the black points shows the sun spot number [14].

3.2. Periodic modulation analysis

In order to search for an unexpected periodic signal of the solar neutrino, we had performed the periodic search analysis using SK-I 1,496 days data set [15]. In the past analysis, we used 5-days binning flux data sample whose energy range is from 4.5 MeV to 19.5 MeV in the recoil electron kinetic energy and applied Lomb-Scargle method to the 5-days sample. Finally, we reported that no significant periodic signal was found. On the other hand, other researches pointed out that the periodic signal at $\sim 9.42 \text{ year}^{-1}$ was observed using the same data set [16, 17]. Their analysis used the generalized Lomb-Scargle method [18] which deals the measurement asymmetric uncertainty properly.

We performed a re-analysis of the SK-I 1,496 days data set [2] and an analysis of the SK-IV 1,664 days data set [8] using the generalized Lomb-Scargle method. The analysis condition is summarized in Table 1.

Table 1. The summary of the periodic signal analysis.

SK phase	SK-I	SK-IV
Livetime	1,496 days [2]	1,664 days [8]
Analysis method	Generalized Lomb-Scargle method	
Binning	5-days	
Analysis kinetic energy	4.5–19.5 MeV	

Figure 3 shows the result of the periodic signal search using the generalized Lomb-Scargle

method. The maximum peak at $\sim 9.42 \text{ year}^{-1}$ is found in SK-I data sample while no significant peak is seen around that frequencies in SK-IV data sample.

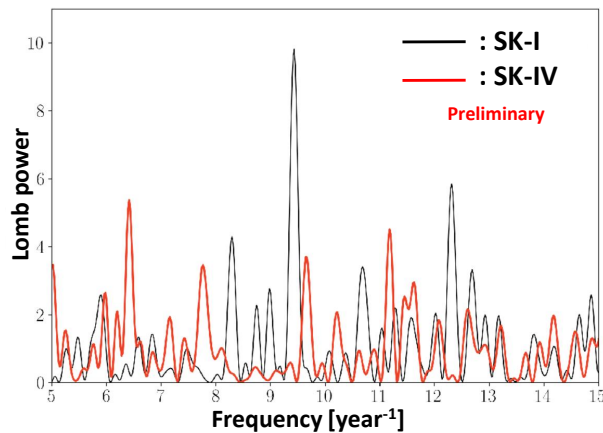


Figure 3. The results of the periodic analysis using the generalized Lomb-Scargle method. The black (red) line shows Lomb power of SK-I (SK-IV) as a function of frequency in unit of year^{-1} . The range of the frequency is from 5 year^{-1} to 15 year^{-1} .

The updated analysis using the data set of SK-II, SK-III and recent SK-IV 2,645 days sample will be performed soon.

4. Energy spectrum measurement

The energy spectrum of recoil electrons are extracted using an extended maximum likelihood fit [8]. Figure 4 shows the combined energy spectrum from SK-I to SK-IV (the end of March 2017, where the livetime of SK-IV is 2,645 days, total livetime of SK is 5,480 days). The total number of energy bins is 23, where 20 bins of 0.5 MeV width between 3.5 MeV and 13.5 MeV, and two bins of 1 MeV between 13.5 MeV and 15.5 MeV, and one bin between 15.5 and 19.5 MeV.

In order to obtain the expected energy spectrum due to the MSW effect, the solar global parameters is determined by referring the solar neutrino experiments from Homestake [19], SAGE [20], GALLEX/GNO [21], SNO [11], Borexino [22, 23, 24] and SK [2, 9, 10, 8]. The solar global parameters are determined $\sin^2 \theta_{12} = 0.308 \pm 0.014$ and $\Delta m_{21}^2 = 4.84_{-0.60}^{+1.26} \times 10^{-5} \text{ eV}^2$. By adding the KamLAND anti-electron neutrino data [25, 26], the solar plus KamLAND parameters are determined $\sin^2 \theta_{12} = 0.316 \pm 0.011$ and $\Delta m_{21}^2 = 7.49_{-0.18}^{+0.19} \times 10^{-5} \text{ eV}^2$. According to neutrino oscillation parameters above, the expected curves of the MSW effect are also shown in Figure 4. Comparing χ^2 between the quadratic best-fit of the data (black) and the predictions (green and blue), the SK recoil electron spectrum is consistent within $\sim 1\sigma$ with the MSW up-turn for the solar global best-fit parameters and marginally consistent within $\sim 2\sigma$ with the MSW up-turn for the solar plus KamLAND best-fit parameters.

5. Summary

The Super-Kamiokande detector has precisely measured the ^8B solar neutrino flux, its time variation and recoil electron spectrum. The ^8B solar neutrino flux is measured to be $(2.355 \pm 0.033) \times 10^6 / \text{cm}^2 / \text{sec}$. No significant correlation between the observed solar neutrino flux and the sun spot number is found. The analysis searching for periodic signals of solar neutrinos has been performed. The maximum peak at $\sim 9.42 \text{ year}^{-1}$ found in SK-I data set has not been found in SK-IV data set. The energy spectrum of recoil electrons is consistent with the MSW prediction by $\sim 1\sigma$ ($\sim 2\sigma$) level for the solar global parameters (solar plus KamLAND parameters).

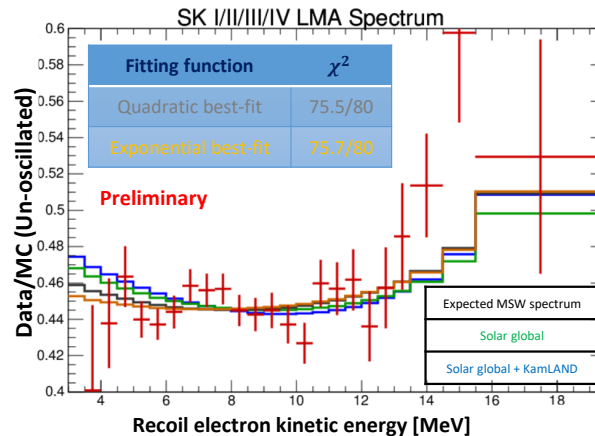


Figure 4. The energy spectrum as a function of the recoil electron kinetic energy combining SK-I through SK-IV until March 2017. The vertical axis shows the ratio between the observed data and the un-oscillated ^8B MC solar neutrino spectrum.

Acknowledgments

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References

- [1] Bahcall J and Ulrich R 1988 *Rev. mod. Phys.* **60** 297
- [2] Hosaka J *et al.* 2006 *Phys. Rev. D* **73** 112001
- [3] Ahmad Q R *et al.* 2001 *Phys. Rev. Lett.* **87** 071301
- [4] Fukuda Y *et al.* 2003 *Nucl. Instrum. Meth. A* **501** 418
- [5] Mikheyev S P and Smirnov A Y 1985 *Sov. Jour. Nucl. Phys.* **42** 913
- [6] Wolfenstein L 1978 *Phys. Rev. D* **17** 2369
- [7] Renshaw A *et al.* 2014 *Phys. Rev. Lett.* **112** 091805
- [8] Abe K *et al.* 2016 *Phys. Rev. D* **94** 052010
- [9] Cravens J P *et al.* 2008 *Phys. Rev. D* **78** 032002
- [10] Abe K *et al.* 2011 *Phys. Rev. D* **83** 052010
- [11] Aharmin B *et al.* 2013 *Phys. Rev. C* **88** 025501
- [12] Cisneros A 1971 *Astrophys. Spa. Sci.* **10** 87
- [13] Voloshin M B, Vysotskii M I and Okun L B 1986 *Sov. Phys. JETP* **64** 446
- [14] WDC-SILSO, Royal Observatory of Belgium, Brussels. <http://www.sidc.be/silso/datafiles>
- [15] Yoo J *et al.* 2003 *Phys. Rev. D* **68** 092002
- [16] Sturrock P A and Scargle J D 2006 *Sol. Phys.* **237** 1
- [17] Desai S and Liu D W 2016 *Astropart. Phys.* **82** 86
- [18] Zechmeister M and Kürster M 2009 *A&A* **496** 577
- [19] Davis R Jr., Harmer D S, and Hoffman K C *et al.* 1968 *Phys. Rev. Lett.* **20** 1205
- [20] Adburashitov J N *et al.* 2009 *Phys. Rev. C* **80** 015807
- [21] Altmann M *et al.* 2005 *Phys. Lett. B* **616** 174
- [22] Bellini G *et al.* 2011 *Phys. Rev. Lett.* **107** 141302
- [23] Bellini G *et al.* 2010 *Phys. Rev. D* **82** 033006
- [24] Bellini G *et al.* 2012 *Phys. Rev. Lett.* **707** 051302
- [25] Abe S *et al.* 2008 *Phys. Rev. Lett.* **100** 221803
- [26] Gando A *et al.* 2013 *Phys. Rev. D* **88** 033001