# Measurement of the Solar Anisotropy with IceCube

THE ICECUBE COLLABORATION[1]

[1]*See special section in these proceedings*

**Abstract:**

IceCube is a kilometer scale neutrino observatory that collects a large number of cosmic ray induced muon events. These events, which are background for neutrino searches, are observed at a rate that is suitable for high-statistics studies of cosmic rays in the Southern hemisphere. The apparent anisotropy created by the motion of the Earth around the Sun, the solar dipole, is systematically analyzed. The solar dipole is simulated, and the predictions for the integrated effect over an entire year and over shorter periods of a quarter-year are compared to data. The experimental observation is found to be in good agreement with the expectation. Finally, we show that the interference between the solar dipole and the sidereal anisotropy is well understood within the statistical uncertainties.

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## 1 Introduction

The motion of an observer in the cosmic ray plasma is predicted to cause an apparent dipole effect in the cosmic ray arrival direction; this effect was first pointed out in 1935 by Arthur Compton and Ivan Getting [1]. Using this principle, the motion of the Earth around the Sun would produce an excess in the direction of motion and a deficit in the opposite direction. This observation was first reported by Cutler in 1986 [2], and then later observed by multiple experiments (i.e. Tibet Air Shower Arrays (Tibet AS$\gamma$) [3], Milagro [4], and EAS-TOP [5]). This measurement is referred to in this contribution as the solar dipole effect anisotropy and is expressed as

$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\frac{v}{c}\cos(\theta_v) \qquad (1)$$

where $I$ is the intensity, $\gamma$ is the differential cosmic ray spectral index, $v$ is the Earth's velocity, $c$ is the speed of light, and $\theta_v$ is the angle between the reconstructed arrival direction of the cosmic rays and the direction of the motion of the Earth [6].

In addition to the solar dipole effect, galactic cosmic ray anisotropies have been observed by underground and surface array experiments in the Northern hemisphere such as Tibet AS$\gamma$ [3]. Furthermore, IceCube recently reported the first observation of the sidereal anisotropy in cosmic ray arrival direction in the Southern sky [7] with a relative

amplitude of the order of $10^{-4}$ to $10^{-3}$. The cosmic ray anisotropy showed that the sidereal anisotropy in the Southern sky is a continuation of that observed in the Northern hemisphere.

In this proceeding, we report on the study of the observation and the expectation of the solar dipole effect in one full year. We also examine the effect of the mutual interference between the sidereal anisotropy and the solar dipole effect by examining quarter-year periods. The solar dipole effect and the interference between the sidereal and the solar effect over quarter-year periods is found to be well understood. This understanding supports the reliability of the sidereal anisotropy observations.

## 2 Data Analysis

IceCube is optimized for the detection of up-going, high-energy neutrinos, however its trigger rate is dominated by down-going atmospheric muons created in cosmic ray air-showers above the detector. In this work, we use the down-going atmospheric muon flux as our signal to study cosmic rays in the Southern sky. The data used in this analysis are the down-going muons collected by the IceCube detector in its 59-string configuration from May 2009 to May 2010. The data are reconstructed by an online maximum likelihood based reconstruction algorithm at an average rate of $\sim$1.2 kHz. A range of selection criteria is applied to the data to ensure detector stability. The final data set consists
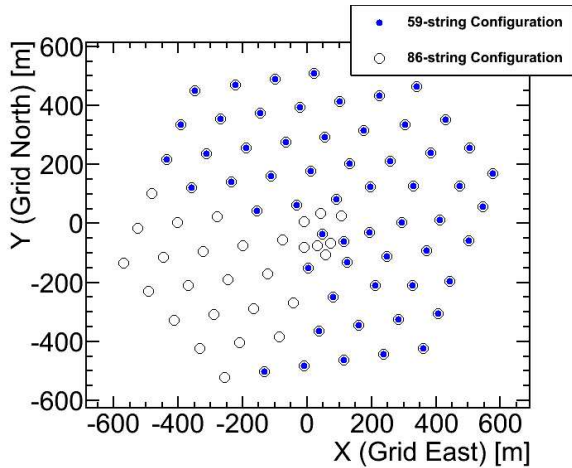
Figure 1: This plot shows the IceCube configuration with 86 strings in empty circles and the 59-string configuration in filled circles.
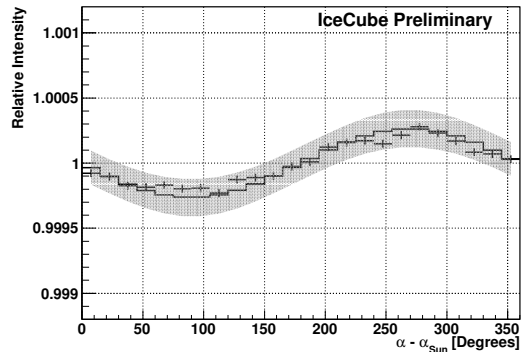


Figure 2: The plot shows the one-dimensional projection in $\alpha - \alpha_{Sun}$ of the relative intensity of cosmic rays. The data are shown with statistical uncertainties in black crosses, and the black line corresponds to the expectation from eq. 1. The gray shaded band indicates the 68% spread of the uncertainty in the simulated solar dipole.

of 33 billion events and corresponds to a detector livetime of 324.8 days. The events are initiated by muons from cosmic ray air-showers with a median primary energy of 20 TeV. The angular resolution between the muon to the primary cosmic ray particle has a median value of $\sim 3°$.

Located at the South Pole, IceCube observes the Southern sky year-round. However, an artificial azimuthal asymmetry occurs as an artifact of the detector's geometrical configuration (Figure 1) combined with non-uniform time coverage. This azimuthal asymmetry was eliminated by re-weighting the azimuthal arrival directions of the incoming cosmic rays [7].

## 3   Solar Dipole Anisotropy Measurement and Expectation

The solar dipole is a well-known signal, both from theory and from observations by other experiments. A measurement of this well-known signal with IceCube strongly supports the reliability of the observation of the sidereal anisotropy with the same detector [8].

The amplitude of the solar dipole depends on the geographical latitude of the observer and on the angular distribution of the detected cosmic ray events at the observatory. Due to the location of the IceCube Observatory at the South Pole, the sky is fully visible at any given time. Therefore, the solar dipole is observed in a reference system where the location of the Sun is fixed, where the latitude coordinate is the declination, and the longitude coordinate is defined to be the difference between the right ascension of the cosmic ray arrival direction and the right ascension of the Sun ($\alpha - \alpha_{Sun}$). In this reference frame, the excess due to the solar dipole is expected to be at 270° and a deficit at 90°.

To verify that the experimental observation of the solar dipole is consistent with the expectation, the predicted projection of the solar anisotropy was calculated for the Ice-

Cube location. Since the observed amplitude of the solar dipole depends on the actual angular distribution of the detected muon events, the calculation of the expectation was performed using the azimuth-corrected experimental data. The expectation of the solar dipole was calculated by computing the relative intensity of the solar dipole through the cosmic ray plasma (through eq. 1). Instead of counting the number of events within a given bin in right ascension from the Sun, we calculated for each event, a mean weight corresponding to the expected relative intensity of the solar dipole.

The uncertainties in the cosmic ray spectral index, in the Earth's velocity, and in the reconstructed arrival direction of the events were included into the calculation of the uncertainty of the expectation. The mean spectral index was evaluated using the all-particle cosmic ray spectrum from [9] and was found to be $2.67 \pm 0.19$. The value used for Earth's velocity was $v = 29.8 \pm 0.5$ km/s, where the error takes into account the spread between the maximum and minimum along the elliptical orbit. The angle $\theta_v$ between the reconstructed direction of the muon events and the Earth's velocity vector at the time the event was detected was evaluated accounting for the experimental point spread function. The expected solar dipole distribution, including the 68% spread in the uncertainty of the expectation, is shown in Figure 2. This figure shows that the observation is consistent with the expectation in both amplitude and phase.

## 4 Interference between the Sidereal and Solar Anisotropy

### 4.1 The Sidereal Anisotropy Interference in the Solar Dipole Anisotropy

A check applied to ensure that the solar dipole was well understood was to compare the expected solar dipole distribution to the observed distribution over the three month intervals (February-April, May-July, August-October, and November-January) with approximately the same detector livetime. However, complications exist in this simple dipole picture because if the data are not collected within an integer number of full years, the solar dipole is expected to be strongly distorted by the sidereal anisotropy [7]. This spurious effect is expected because the sidereal reference frame is defined where the celestial sky is fixed, while the solar reference frame is defined where the Sun is fixed. It takes about four fewer minutes to complete a sidereal day than a solar day. Therefore, a static point in the sidereal reference frame will move across the solar frame and return to the same position on the sky in one full year (this is observed implicitly in Figure 2). Therefore, any static sidereal distribution averages to zero in the solar reference frame after one year but not over partial time intervals of the year.

The points with their statistical errors in Figure 3 show the $\alpha - \alpha_{Sun}$ projection of the data collected in the time interval between February and April. The black line shows the solar dipole expectation from the motion of the Earth around the Sun for the same time interval. This illustrates the effect of the distortion by the sidereal anisotropy in the solar dipole. The plot shows that the observation in the solar reference frame is not in agreement with what is expected from the solar dipole alone and is strongly distorted by the sidereal anisotropy.

To eliminate such contamination, the experimental sidereal anisotropy distribution was used to determine how it would look like in solar reference frame. Specifically, a numerical calculation was performed where, every $100\mu s$, an event was generated with a unique UTC time and with right ascension from the all-year experimental sidereal distribution. The corresponding distribution in $\alpha - \alpha_{Sun}$ was determined for the February-April time period and is shown in Figure 4. Once the sidereal anisotropy effect in the solar reference frame is known, it is then subtracted from the distribution measured in the solar reference frame.

Figure 3 shows the distorted cosmic ray distribution in the solar reference frame, and Figure 5 shows the distorted distribution minus the sidereal interference. The plot shows that the data, after correcting for the sidereal effect, is in agreement with the solar dipole expectation for the period from February to April. This effect was also estimated for each of the next three time intervals (May-July, August-October, and November-January) using the same method. The data was found to be in agreement with the expectation within statistical fluctuations.
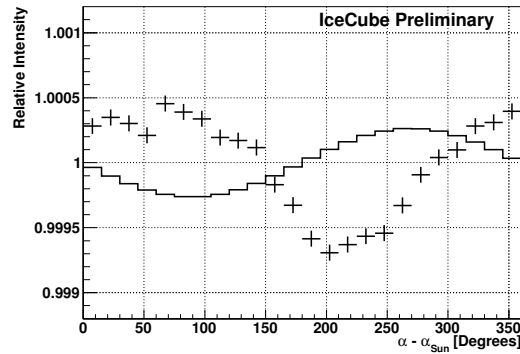
Figure 3: This plot shows the relative intensity of the one-dimensional projection of right ascension with respect to the Sun. The observed cosmic ray events in the period from February to April are shown with statistical uncertainties in the black crosses, and the black line is the relative intensity of the expected solar dipole for the same time period.
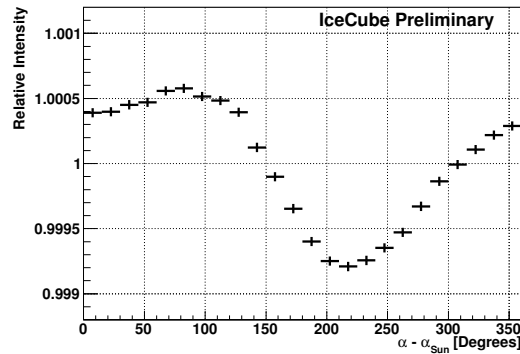
Figure 4: This plot shows the relative intensity of the sidereal anisotropy as it would appear in $\alpha - \alpha_{Sun}$ projection from February to April in absence of the solar dipole. The error bars are the statistical uncertainties.

### 4.2 The Solar Dipole Anisotropy Interference in the Sidereal Anisotropy

Similarly, the effect of the solar dipole interference in the sidereal anisotropy was also checked. This check allows for a better estimate of the systematic effect of the seasonal variation dependence in the sidereal anisotropy of the cosmic ray arrival direction [7]. If the relative intensity in equatorial coordinates is measured over a full year, then the observed sidereal anisotropy is devoid of any distortions by the solar dipole as explained previously. However, similar to the observation of the solar dipole in a quarter-year, we observe (as shown in Figure 6) that the sidereal anisotropy measured in the three month periods between February and March (in gray points) deviates from the full dataset observation (in black line).

This deviation is smaller than the solar dipole's distortion and is consistent with what we would expect. If the same sidereal-to-solar transformation procedure used previously
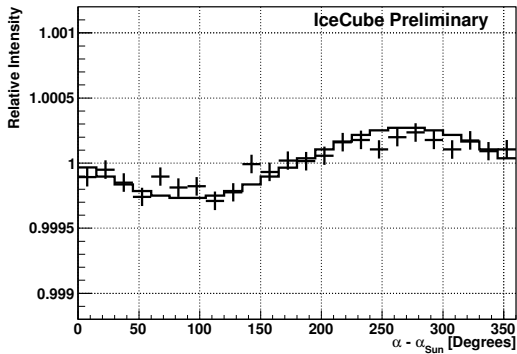
Figure 5: This plot shows the relative intensity of the one-dimensional projection in right ascension with respect to the Sun. The observed cosmic ray events with their statistical uncertainties in the period from February to April minus the propagated sidereal anisotropy in the solar reference frame for same time period are shown in black crosses. The black line is the relative intensity of the expected solar dipole.
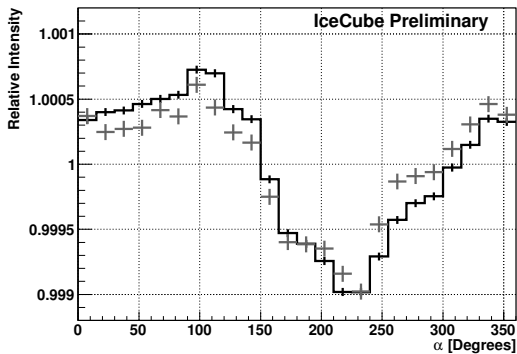


Figure 6: This plot shows the relative intensity of the one-dimensional projection of right ascension. The gray crosses are the observed cosmic ray events in the sidereal reference frame in the period from February to April. The black line is the relative intensity of the same sidereal anisotropy except over the full year. Both the full year and the quarter-year projections are plotted with their statistical error bars.

is applied, but for the sidereal anisotropy, then the solar dipole contribution from the sidereal observation is eliminated as shown in Figure 7. This effect was also corrected for the next three time intervals (May-July, August-October, and November-January) using the same method. The corrected sidereal anisotropy over each of the time intervals was also found to be in agreement with that observed over a full year.

## 5    Conclusion

In this contribution, we presented the observation of the solar dipole using the data collected by the 59-string configu-
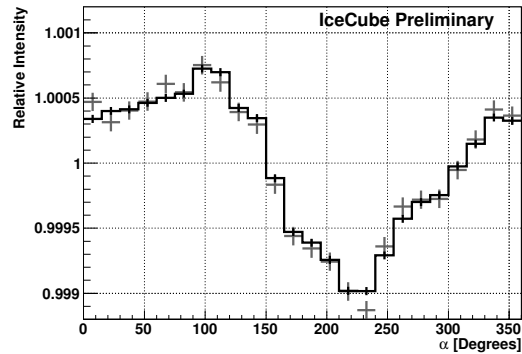


Figure 7: This plot shows the relative intensity of the one-dimensional projection of right ascension. The gray crosses are the observed cosmic ray events in the sidereal reference frame in the period from February to April minus the propagated solar anisotropy in the sidereal reference frame for same time period. The black line is the relative intensity of the same sidereal anisotropy except over the full year. Both the full year and the quarter-year projections are plotted with their statistical error bars.

ration of IceCube from May 2009 to May 2010. The solar dipole effect is studied in one full year and in 3 months intervals. The observed solar dipole in these time intervals was found to be consistent with what is expected from the motion of the Earth around the Sun in both amplitude and phase. The solar dipole effect is a well understood measurement that confirms, within statistical uncertainty, the reliability of the large-scale sidereal cosmic ray anisotropy observations.

## References

[1] Compton, A. H., & Getting, I. A. Physical Review, 1935, **47**: 817.
[2] Cutler, D. J., & Groom, D. E., Nature, 1986,**322**, 434.
[3] Amenomori et al., Science, 2006, **314**: 439.
[4] Abdo et al., Astrophys. J., 2009, **698**: 2121.
[5] Aglietta et al., Astrophys. J., 2009, **692**: L130.
[6] Gleeson, L. J., & Axford, W. I. Ap&SS, 1968, **2**: 431.
[7] Abbasi et al., Astrophys. J., 2010, **718**: L194.
[8] IceCube Collaboration, paper 0305, these proceedings.
[9] Hörandel, J. R., Astroparticle Physics, 2003, **19**: 193.