Measurement of the Solar Dipole with IceCube

The IceCube Collaboration
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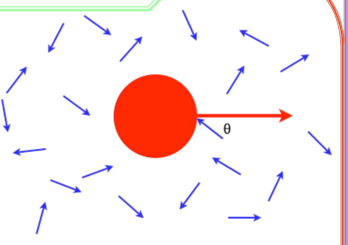
ABSTRACT: IceCube is a kilometer scale neutrino observatory that collects a large number of cosmic ray induced muon events. These events, which are background for neutrino searches, are observed at a rate that is suitable for high-statistics studies of cosmic rays in the Southern hemisphere. The apparent 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.

INTRODUCTION



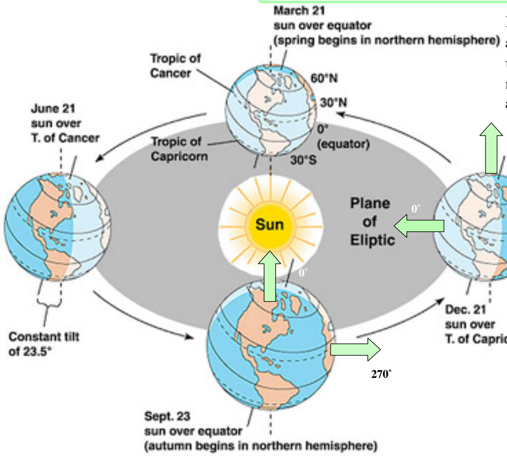
The motion of the Earth around the Sun causes the same effect as a car moving through a rainstorm, that is, an observation of an excess of material toward the front, and a deficit towards the rear.

This expected anisotropy in arrival direction of incoming cosmic rays will be referred to as the "solar dipole" and is expressed through the following equation:

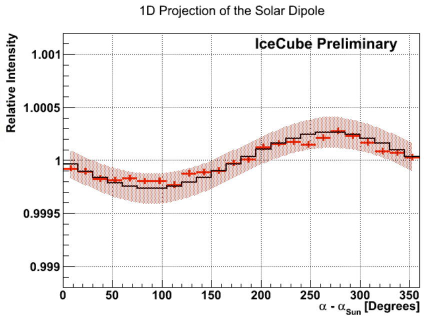
$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\frac{v}{c}\cos\theta$$

Where,
$\gamma = 2.7$ *spectral index of CR*
c = *speed of light*
θ = *angle between observed event and the velocity vector*
$v = 29.78\ km/\text{sec}$
(*Earth's revolution velocity*)

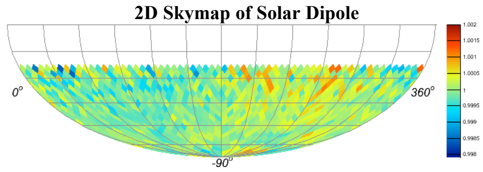
SOLAR DIPOLE ANISOTROPY AND MEASUREMENT



From the figure to the left, we see that the solar dipole is observed in a reference system where the location of the Sun is fixed, and where 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 ($\alpha - \alpha_{Sun}$).



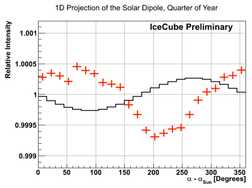
The plot above shows the solar dipole constructed from 12 months of 59-String, IceCube data. The data are shown with statistical uncertainties in red crosses, and the black line corresponds to the expectation. The uncertainties in the cosmic ray spectral index (2.67 ± 0.19), in the Earth's velocity (29.8 ± 0.5 km/s), and in the reconstructed arrival direction of the events (the angle, θ, was evaluated accounting for the experimental point spread function which has a median angle of 3°) were included into the calculation of the uncertainty of the expectation (the red shaded band). This plot shows the agreement between experimental data and simulation.



INTERFERENCE BETWEEN THE SOLAR AND SIDEREAL ANISOTROPIES

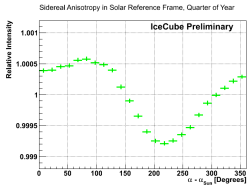
1) SIDEREAL ANISOTROPY IN SOLAR DIPOLE

A check applied to ensure that the solar dipole is 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. 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 black line in the plot in the section to the right shows the sidereal anisotropy. Also see proceeding 305.

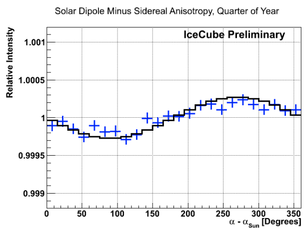


The points with their statistical errors in the figure to the left show the $\alpha - \alpha_{Sun}$ projection of the data collected in the time interval between February and April. The black line shows the solar dipole expectation from the motion of the Earth around the Sun for the same time interval. This illustrates the effect of the distortion by the sidereal anisotropy in the solar dipole.

To eliminate such contamination, the experimental sidereal anisotropy distribution was used to determine how it would look like in solar reference frame. 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.

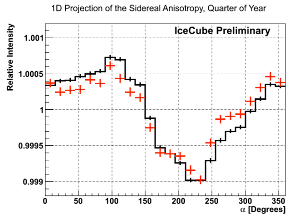


The upper left figure shows the distorted cosmic ray distribution in the solar reference frame, and the figure below shows the distorted distribution minus the sidereal interference. This plot shows that the data, after correcting for the sidereal effect, is in agreement with the solar dipole expectation for the period from February to April. This effect was also estimated for each of the next three time intervals using the same method. The data was found to be in agreement with the expectation within statistical fluctuations.

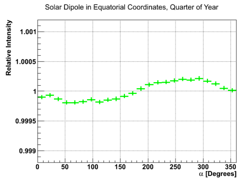


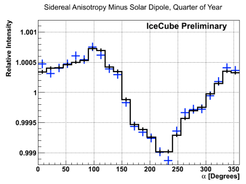
2) SOLAR DIPOLE IN SIDEREAL ANISOTROPY

Similarly, the effect of the solar dipole interference in the sidereal anisotropy was also checked. 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 below) that the sidereal anisotropy measured in the three month periods between February and March (in red points) deviates from the full dataset observation (in black line).



If the same sidereal-to-solar transformation procedure used previously is applied, but for the sidereal anisotropy, then the solar dipole contribution from the sidereal observation is eliminated as shown in the figure on the bottom right. 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.





CONCLUSION: We presented the observation of the solar dipole using the data collected by the 59-string configuration 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.