First geomagnetic storm ever observed from the Middle East using cosmic rays

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***Abstract*—The Global Muon Detector Network (GMDN) was completed by installing a multi-directional cosmic-ray muon hodoscope in Kuwait University in March 2006. The GMDN is currently consisting of four multi-directional muon detectors located at Nagoya (Japan), Hobart (Australia), Sao Martinho (Brazil) and Kuwait University (Kuwait). This Network is continuously monitoring the galactic cosmic rays intensity in a total of 60 directional channels covering almost the entire sky. It represents an important tool for forecasting geomagnetic storms several hours in advance. We recorded the first solar storm ever detected in the Middle East, on 14 December, 2006. It produced a severe geomagnetic storm that sparked Northern lights as far as Arizona. This geomagnetic storm induced electric currents that flow from oil pipelines into the soil which corrode pipes faster than normal.**

1. GLOBAL MUON DETECTOR NETWORK (GMDN)

The muon network construction started in December 1992 after adding a muon detector at Hobart (Australia) to the detector located at Nagoya (Japan). The detection areas of these detectors are 9 m^2 and 36 m^2 respectively. Each of these detectors is multidirectional, allowing us to simultaneously record the intensities in 30 directions of viewing. Next, the network is expanding by adding a third small (4 m^2) prototype detector at Sao Martinho (Brazil) in March 2001 to receive muons over the Atlantic and Europe. This prototype Sao Martinho was then upgraded in December 2005 by expanding its detection area to 28 m^2. Finally we completed the GMDN by installing a new detector at Kuwait University in March 2006. This adds new directions of viewing over the African Continent and the western Indian Ocean. The Kuwait University muon detector is a hodoscope designed specifically for measuring the “loss cone” anisotropy, which is observed as a precursor to the

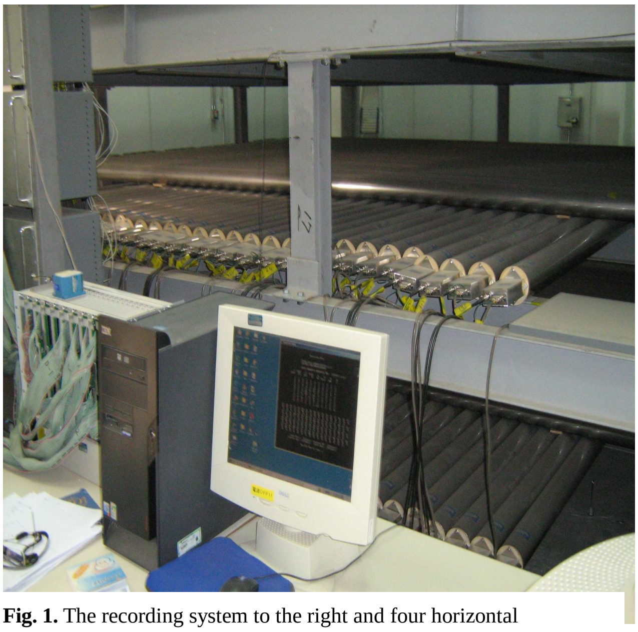

Fig. 1. The recording system to the right and four horizontal layers with 30 PCTs in each layer to the left.

arrival of interplanetary shocks at Earth and is characterized by an intensity deficit confined to a narrow pitch angle region around the sunward interplanetary magnetic field direction. Unlike the other three detectors, the Kuwait University detector (Figure 1) consists of four horizontal layers of 30 proportional counter tubes (PCTs) in each layer. Each PCT is a 5 m long cylinder with a 10 cm diameter having a 50-micron thick tungsten anode along the cylinder axis. A 5 cm layer of lead is installed above the detector to absorb the soft component radiation in the air. The PCT axes are aligned geographic east-west (X) in the top and third layers and north-south (Y) in the second and bottom layers. The top and second layers form an upper pair, while the third and bottom layers form a lower pair. The two layers in each pair are perpendicular to each other and cover

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(3mX3m) area. The two pairs are separated vertically by 80 cm. Muon recording is triggered by the fourfold coincidence of pulses from all layers and the incident direction is identified from X-Y locations of the upper and lower PCT pairs. The muon count is recorded in each of 23×23=529 directional channels which cover 360° of azimuth angle and 0°

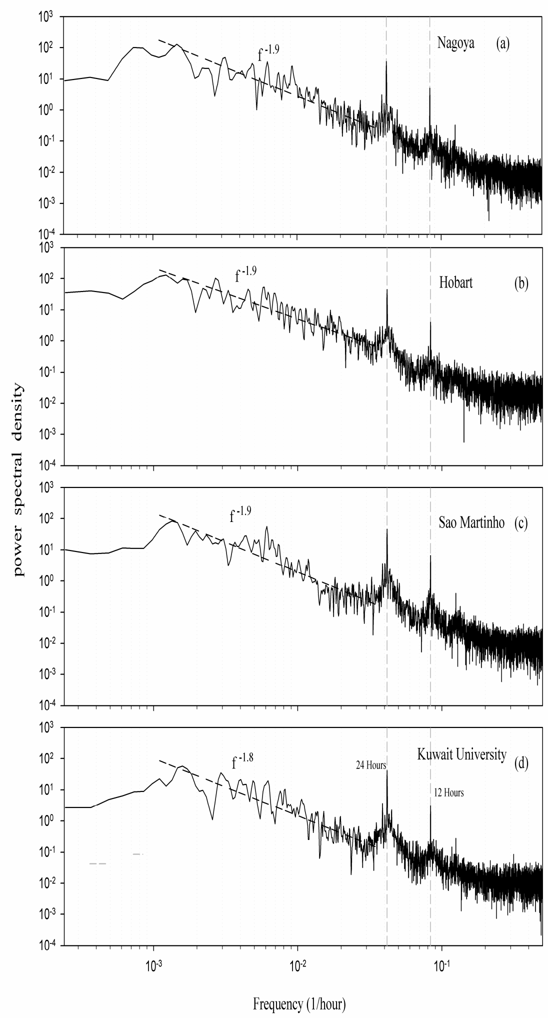

Fig. 2. Power spectra density of the cosmic ray scintillations observed in the vertical channels in the GMDN: (a) Nagoya (Japan) (b) Hobart (Australia) (c) Sao Martinho (Brazil) and (d) Kuwait University.Note that the amplitudes of the diurnal and semidiurnal variations are well defined at the 4 detectors. The best fit for the spectra (f^{-n}) is shown for f < 0.03 c/hour.

to 60° zenith. For analyzing Kuwait University data together with the data from the other three detectors of different geometry, we convert 529 directional channels into 13 channels, which are equivalent to those in Hobart having the same detection area (9 m^2). GMDN covers almost the entire sky. The hourly average counts observed with each detectors are corrected for pressure and plotted regularly every day at: http://neutronm.bartol.udel.edu/spaceweather/

2. COSMIC RAY VARIATION

[1] developed a new analysis method to eliminate the atmospheric temperature effect on the muon count rate. This method enables them to compare the derived spatial gradient of the cosmic ray density with the prediction of the drift model. The three components of anisotropy ($\xi^{GEO}_x(t)$, $\xi^{GEO}_y(t)$, $\xi^{GEO}_z(t)$) in local geographical coordinate system are calculated by fitting the function:

$$I^{fit}_{i,j}(t) = I^{0}_{i,j}(t) + \xi^{GEO}_x(t)[c^{1}_{1i,j}\cos\omega t_i - s^{1}_{1i,j}\sin\omega t] + \xi^{GEO}_y(t)[s^{1}_{1i,j}\cos\omega t_i + c^{1}_{1i,j}\sin\omega t] + \xi^{GEO}_z(t)\, c^{0}_{1i,j} \qquad (1)$$

to the observed hourly count rate $I^{obs}_{i,j}(t)$ of muons at universal time (t) in the j-th directional channel of the i-th muon detector in the GMDN. Next, we transform the above three components of anisotropy into Geocentric Solar Ecliptic coordinates system and then corrected for the solar wind convection and the Compton-Getting anisotropy arising from the Earth's 30 km/s orbital motion.

3. MAXIMUM ENTROPY ANALYSIS

[2] related the fluctuations of cosmic ray intensity (cosmic ray scintillations) observed with neutron monitors over the low frequency range $10^{-7}\,Hz \le f \le 10^{-4}\,Hz$ to fluctuation in the interplanetary magnetic field (IMF). They derive a theoretical model which attributes the cosmic ray scintillations caused by turbulent magnetic field in the interplanetary medium. Here we use pressure-corrected hourly mean cosmic ray counting rates observed in the vertical channel to estimate the power spectral density (PSD) for each muon detector. We use Maximum entropy method to estimate the PSD. This method is more powerful than traditional Fast Fourier Transform method [3]. Figure 2 displays the PSD for each detector in the network during the period March 2006 to December 2007. During this period, the IMF points toward the Sun north of the heliospheric current sheet and away from the Sun south of it (qA<0). The dashed straight line in each panel represents the best fit power law (f^{-n}) for the spectra. The slope of the best fit line is ~ 1.9 for frequency $f < 10^{-3}$ Hz. This agrees with the results obtained by [3] using cosmic ray intensity observed with Mawson underground muon detector during years of negative solar polarity qA<0 (1981–1988). They found that the spectra are steeper and have higher power when qA<0 than when qA>0. The first two harmonics of the solar daily

variation are well defined at 24 hours (diurnal) and 12 hours (semi-diurnal) (see vertical lines in Figure 2

4. COSMIC RAY PRECURSORS OF GEOMAGNETIC DISTURBANCES

Our network recorded a reduction in muon counts on 14 December 2006, indicating the arrival of interplanetary shocks and the associated interplanetary coronal mass ejection (CME) at Earth. Figure 3 shows a rapid Forbush Decrease in the intensity of muons observed by the four detector of the GMDN on 14 December. This decrease was due to the intense magnetic field associated with the CME that swept some of galactic cosmic rays away from Earth. The cosmic ray intensity returned back to normal on the19 December. This depression coincides with a pronounced enhancement of the estimated (3-hourly) geomagnetic *Kp* index reaching values of 7 during 15-18 hours UT and of 8 during 21-24 hours UT. A clear "loss-cone" precursor has been observed in the muon data that appeared on 14 December 2006 at 7:00 hours UT in the vertical channel of the Sao Martinho muon detector in Brazil (Figure 3c). The lead time of this precursor is about 7 hours prior to SSC indicating the shock arrival at Earth. This event produced a strong geomagnetic storm that sparked Northern lights as far as Arizona. Observation of high energy Cosmic ray by GMDN can be used as an alert for space weather events. It will allow early determination of space weather storms. One of the major objectives is to forecast the arrival of the geomagnetic storm. Figure 4 shows another possibility of the GMDN providing alert well before the geomagnetic disturbance with SSC onset on. The depression of the Z-component of the anisotropy (Figure 4c) is seen half a day before SSC.

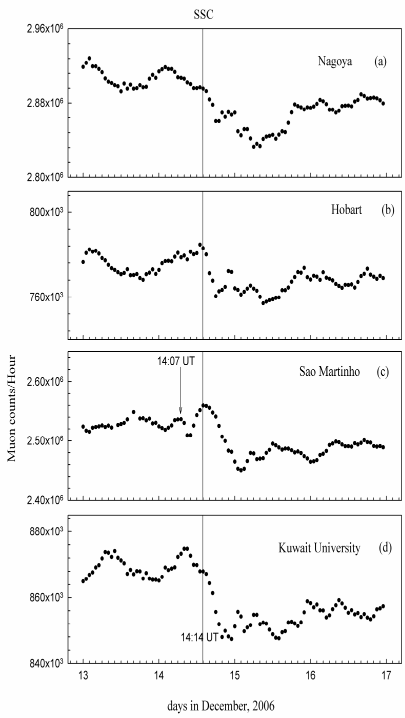

Fig. 3: Forbush decreases observed right after the SSC onset in four vertical channels of the GMDN. In (c) a clear loss-cone signature observed by Sao Martinho muon detector prior to the SSC causing a severe geomagnetic storm in Figure 4.

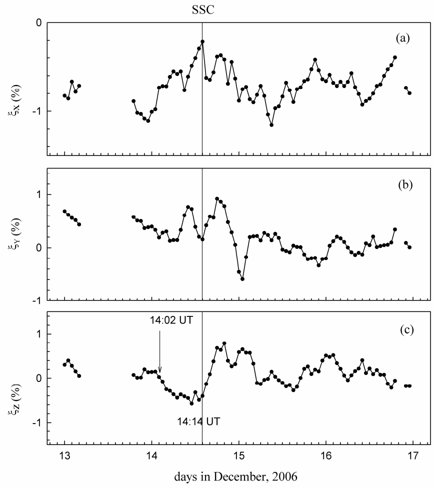

Fig. 4: A depression of the z-component anisotropy clearly seen12 hours prior to the onset of SSC and the geomagnetic storm on 14 December, 2006.

5. SUMMARY AND CONCLUSIONS

We completed the GMDN by installing a multi-directional cosmic-ray muon hodoscope at Kuwait University in March 2006. Hourly averaged values of cosmic ray counts observed with the GMDN have been analyzed during the period March 2006 to December 2007. The three components of anisotropy of galactic cosmic rays have been computed every hour and corrected for pressure and temperature effects. Maximum entropy method has been used to estimate the PSD of the hourly data for each station. The first two harmonics of the solar daily variation are well defined. The GMDN aims to predict the changes in Space Weather from ground–based measurements of cosmic rays. The onset of cosmic ray precursor can provide us with a tool for predicting the space storms. Early detection of space weather storms is essential to avoid significant problems in space as well as on Earth. A loss-cone precursor was recorded by the GMDN about 7 hours before the geomagnetic storm onset in 14 December, 2006. This storm was caused by a strong shock accompanying a coronal mass ejection and forming a depleted region of galactic cosmic rays behind it. This was the first geomagnetic storm ever observed from the Middle East using cosmic rays. It produced a severe geomagnetic storm that sparked Northern lights as far as Arizona. This geomagnetic storm must have induced electric currents that flow from oil pipelines into the soil which corrode pipes faster than normal. We are planning to install a magnetometer to measure variations in the geomagnetic field. This will give us a chance to compare this variations with that in the pipe-to-soil potential difference during magnetic storms.

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