H.E.A.M.S., the Adelaide High Energy Astrophysics Muon System.

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Introduction

For many years, there have been astrophysical muon detection systems operated at the University of Adelaide. The Adelaide detectors have recently been rebuilt and upgraded with a new data acquisition system to become HEAMS.

Such muon systems are sensitive to the flux (number per square metre per second) of low energy galactic and solar cosmic rays which reach our upper atmosphere after passing through the Sun's heliosphere from interstellar space. The Sun is surrounded by a mixture of ionised gas and magnetic fields (known as a plasma) in the turbulent 'solar wind' which extends out to about one light day from us. Galactic cosmic rays (energetic charged nuclei) reach us after passing in through this plasma, but the number which complete that journey depends on their energy and the conditions in the solar plasma. As a result, the measured flux of cosmic rays is related to the conditions within the heliosphere. These, in turn, depend on the level, and type, of solar activity.

There is a daily variation in the number of detectable particles since the solar magnetic field influences the flow of charged cosmic rays in the vicinity of the Earth. Those solar magnetic field 'lines' follow a spiral pattern because of the continual rotation of the Sun, and arrive at the Earth in a direction (nearly at right angles to the Sun's direction – 'noon') such that there is a slight maximum in intensity at mid- to late afternoon. If this effect is allowed for, or averaged out over a sidereal ('by the stars') year, the underlying galactic direction (the 'sidereal anisotropy') can be found.

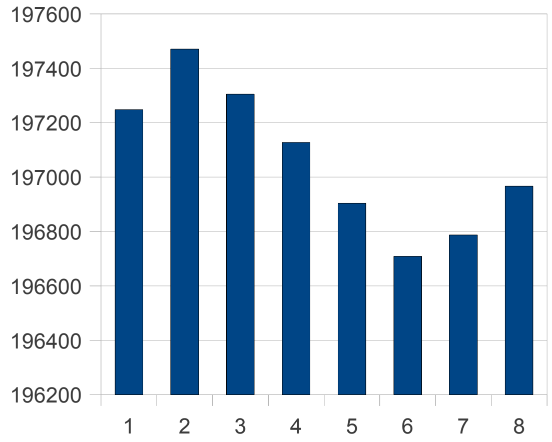


Figure The variation over a solar day of the muon rate. This is the average over 2005. The data are count numbers (divided by 900) in three hour solar intervals (in Universal Time – so local time at Adelaide is that time plus 9.5 hr). The peak is around 4.5 hr UT which is 2 p.m. Local time. Note that each interval contains about 200 million counts. The variation range is about 700/197000 or about 0.35%

It is possible to measure the variation in the count rate in terms of time relative to the stars (sidereal) rather than the sun (solar). This measurement is much more difficult and the effect can be masked by the larger solar signal and irregular solar transient events. The peak (figure below) is around 6 hr sidereal, which implies an excess of cosmic rays from the general direction of 6 hr right ascension at the latitude of Adelaide. Note that each interval contains about a billion counts (multiply the 'y' axis by 900. The variation range is about 350/970000 or about 0.035%

Because of the solar and heliospheric processes which contaminate the data, a correction must be made to these data to obtain a 'true' sidereal amplitude and direction. For the period 2004-2008 the true sidereal 'vector' has an amplitude in the range 0.02-0.04% and a direction of about 9 hr right ascension.

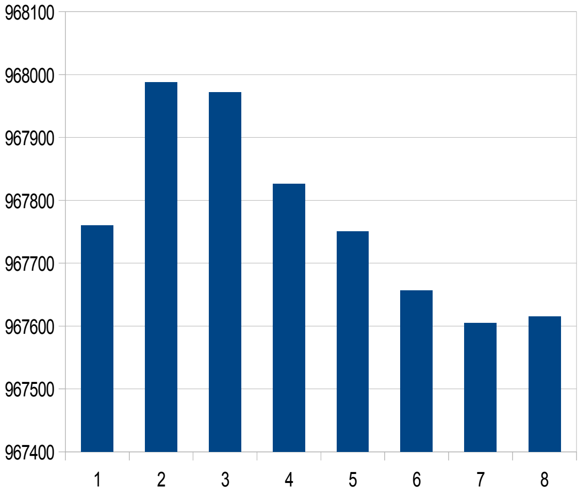
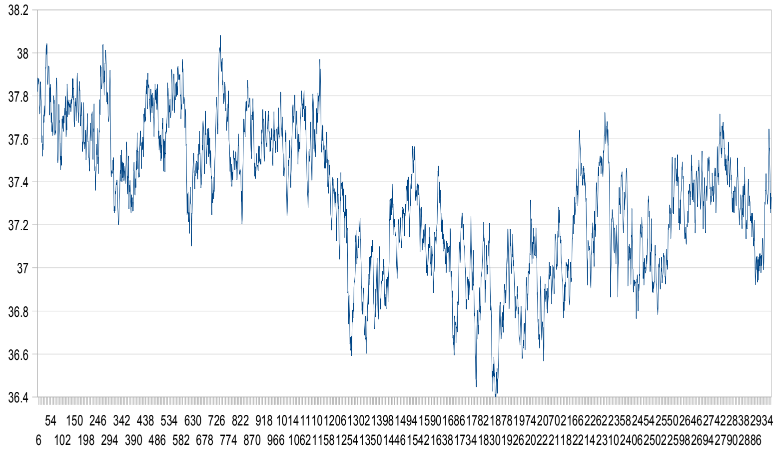


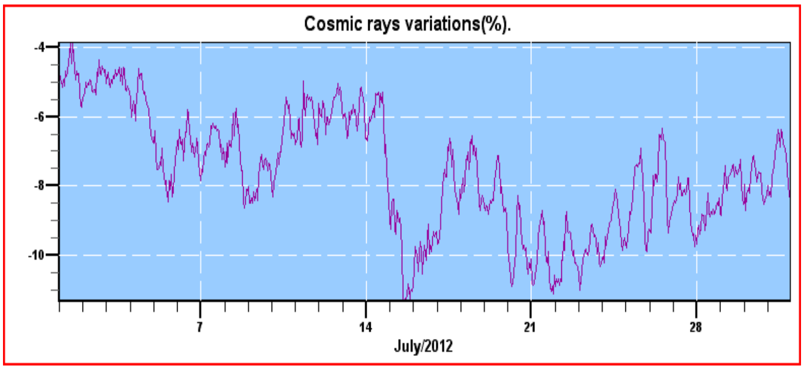
Figure The variation over a sidereal (by the stars) day of the muon rate. This is the average over 2004-2008 (5 years). The data are count numbers (divided by 900) in three hour sidereal time intervals.

Transient Events

Our Sun can exhibit major energetic events (solar flares, Coronal Mass Ejections (CMEs)) which can affect the number of cosmic rays which reach theEarth. The flare produces plasma with embedded magnetic fields that inhibit the flow of cosmic rays. If this plasma approaches, or envelops, the Earth, the rate of arrival of cosmic rays drops a little. This process is often known as a Forbush Decrease.



Adelaide Muon Data



Moscow data (http://cr0.izmiran.rssi.ru/mosc/main.htm)

Figure Data from the Adelaide muon system and from the Moscow Neutron Monitor for July 2012 when the Sun was in an active state. Note the similarities but remenmber that Adelaide views the sky at a different time from Moscow (because of its longitude) and in a different direction (because of its latitude) so the differences tell us things about the distribution of plasma in the CME around us.

Detecting Cosmic Rays

When the cosmic rays enter our atmosphere, they interact with ('hit') atmospheric nuclei (nitrogen or oxygen) and those interactions produce nuclear particles known as pions which quickly decay into muons. In passing down through the atmosphere, those muons lose energy but, on the whole, do not suffer catastrophic interactions. Many of those muons reach the ground and can be detected using conventional radiation detectors. Roughly speaking, the rate of muons arriving at sea level is about one per square centimetre per minute, about 160 Hz for a one square metre detector.

At Adelaide, we have two 'scintillator' detection systems. One, based at the University campus in the city CBD, has an area of one square metre and measures muons which have passed roughly vertically through three concrete floors of a building ('Adelaide Vertical'). The other is based 45 km north of the City of Adelaide and consists of eight one square metre detectors arranged in two layers ('uppers' and 'lowers'), each of which has four detectors. These layers are arranged above each other so that, by taking 'coincidences', we can select muons (and their parent cosmic rays) which came from any of nine possible diagonal or vertical (or just broadly down wards) directions.

Since we have four independent detectors in a layer, we can select to have them detect low energy cosmic ray showers by demanding that any three out of four detectors register particles at the same time (3 from 4 coincidences).

Data are recorded every 15 minutes. At that time, the number of counts in each detector, and the number of coincidences in each of the arrival directions are recorded. That number ranges from a total of over a million, if all possible independent muons are counted, down to a few hundred for the 3 from 4 coincidences. Raw count data are appended to a monthly file through each month (heams.txt), and a new file is created at the start of each successive month.

Since the muons which penetrate the atmosphere and are then detected below some concrete floors in the Campus building, one can estimate the average energy of the initial cosmic rays which contribute to the measurement. E.Eroshenko, M.Berkova, R Clay, and V.Yanke showed in a 2013 International Cosmic Ray Conference paper that the typical primary energies detected by HEAMS were about 60 GeV for vertical muons.

Pressure Coefficients

The number of particles (muons) which pass through the atmosphere depends on the amount of atmosphere between the detector and the 'top' of the atmosphere. When the atmospheric pressure changes (the 'weight' of the atmosphere above), that vertical amount of atmosphere (uaually measured in grams per square centimetre) also changes, and changes most for oblique, high angle, arrival directions. For display, we calculate a 'pressure coefficient' for each direction and 'correct' our data for pressure variations. The variations in the displayed data are then mainly due to the influence of the variations in the conditions of the Sun and its heliosphere.

(Actually, the atmospheric temperature and pressure at the height of production of the muons – about one tenth of the way through the atmosphere – affects the number of muons which are produced and so there is an additional small annual effect due to seasonal temperature changes in the upper atmosphere.)

So, the atmosphere acts as an absorber for muons which are produced through cosmic ray interactions high in the atmosphere. As a result, a number of atmospheric properties can affect the rate of detection on muons. In order to study the heliosphere, the most significant of these need to be compensated for. The first, and most important, thing to do is to correct for pressure effects. As we saw, the pressure is related to the bulk of atmospheric gas above the detector so the rate of muon detection reduces as the pressure increases, and this effect is strongest when the arrival direction isaway from the zenith and the muons traverse more atmosphere – 'diagonal' directions.

Approximate (negative) pressure coefficients (units of %/hPa or %/mb) are:

Vertical	0.10
uppers/lowers	0.14
Diagonals (sides)	0.18
Diagonals (corners)	0.24
¾ small showers	0.40
'veto' small showers	0.60

These are currently under revision as more data become available.

Data labelling for internet-accessible HEAMS data:

Adelaide data are from two one square metre scintillators diectly above each other. If we demand that a muon has travelled through both scintillators, we refer to these as 'vertical' muons. If we simply count all muons in a single detector, we refer to these as 'singles'.

At Buckland Park, there are four scintillators vertically above another group of four in a light-tight dark room. One layer is shown below.

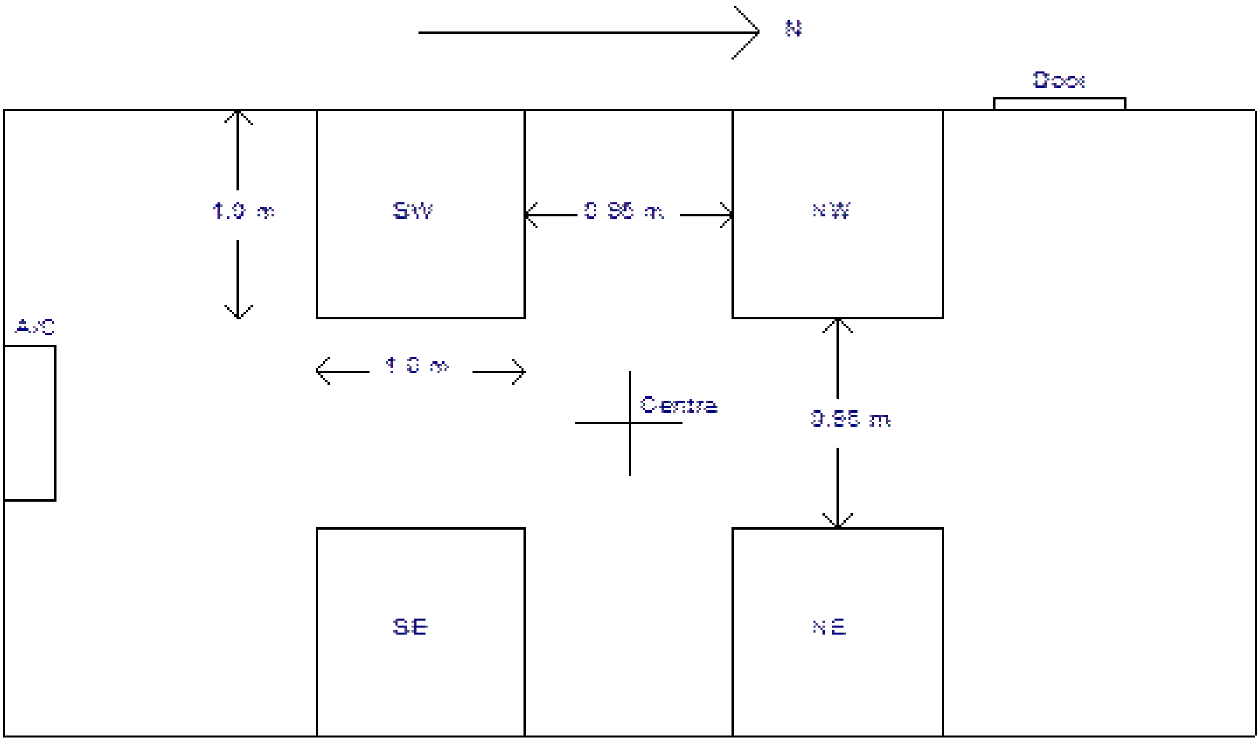


Figure. Layout of the Buckland Park muon system. The system has two layers of scintillators in the positions SW, NW, SE, NE. Muons can be selected which pass through preset combinations of detectors in order to give different viewing directions. The detectors can also be used individually to detect very low energy cosmic rays, or in combinations of many detectors to record low energy cosmic ray showers.

The top layer is labelled 'uppers' (U), the bottom layer is labelled 'lowers'(L). The four scintillators in a layer are labelled : North West (NW), North East (NE), South West (SW) and South East (SE). So, for instance, USE is the upper South East scintillator and is directly above LSE.

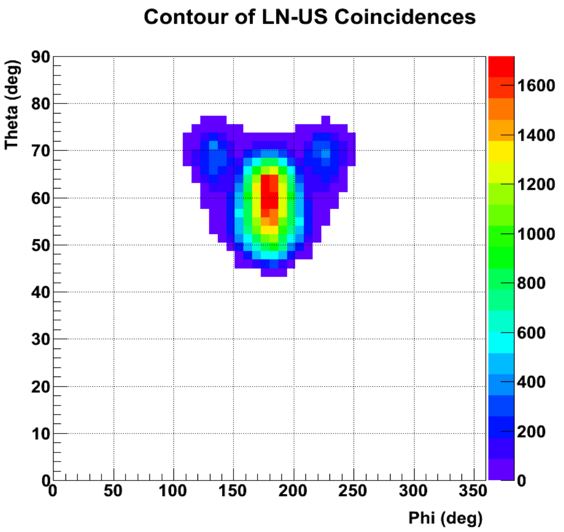


Figure. Arrival direction distribution (azimuth and zenith angle) for coincidences between an upper north detector (e.g.,UNW) and a corresponding lower south detector (LSW in this case).

Side diagonals would be, for instance, a coincidence between UNW and LSW OR UNE and LSE. That combination would produce a 'beam' which is roughly equatorial (Buckland Park is at a latitude of about 35 degrees south). Reversing S and N would give a beam roughly towards the South Pole direction.

Corner diagonals, such as UNE+LSW give data from a larger zenith angle across the system (four directions). Since the corner diagonal directions use only a single pair of scintillators (two pair are used for the side diagonal directions), and the angle from the zenith is greater, the rate of muons for the corner diagonal directions is quite low, about 1 Hz.

It is possible to take a coincidence of three out of four scintillators in the top layer (“3 from 4” coincidences) . This is sensitive to small showers, not muons.

It is possible that small showers might produce an accidental coincidence which would look like a muon signal. We reduce these accidentals by couinting the number of times any third scintillator is also in coincidence with the specified scintillators. These are labelled 'vetos' and their rate can be subtracted from the total coincidence rate of a certain kind. (Of course, such vetoes can be usefully counted as another measure of the rate of arrival of small (low energy) showers and so, summing veto rates can give a useful measure of the rate of low energy cosmic ray showers).

We are also have a second by second total counting rate monitor to enable us to for search for gamma-ray burst (GRB) coincidences.

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For data collected from December 2013 - HEAMS data

Data columns (These are BOTH tab and comma separated):

A	Date (UTC)
B	Time at start of interval (UTC)
C	Adelaide temperature (°C)
D	BP temperature (°C)
E	Adelaide pressure (hPa)
F	Adelaide verticals
G	upper 3/4
H	uppers
I	lowers
J	totals
K	verticals
L	US-LN
M	US-LN veto
N	UN-LS
O	UN-LS veto
P	UE-LW
Q	UE-LW veto
R	UW-LE
S	UW-LE veto
T	USW-LNE
U	USW-LNE veto
V	UNE-LSW
W	UNE-LSW veto
X	USE-LNW
Y	USE LNW veto
Z	UNW-LSE
AA	UNW-LSE veto
AB	Adelaide singles
AC	UNE
AD	LNE
AE	USE
AF	LSE
AG	USW
AH	LSW
AI	UNW
AJ	LNW

Comment on the history of the datsaet.

E.Eroshenko, M.Berkova, R Clay, and V.Yanke showed in a 2013 International Cosmic Ray Conference paper that, from 2004 to 2012, the Adelaide detector of HEAMS progressively lost efficiency at a rate of 2.7% / yr. The detector was rebuilt and it was found that one of the component scintillators (four 500x500 mm, making up a complete one square metre) had deteriorated. This was replaced in 2013.

The original Buckland Park system was installed by Neville Wild, Roger Clay, and Abdullrahman Maghrabi in the late 1990s.

The new HEAMS system was installed and tested over 2013 and 2014. It had problems with channels upper NE and upper NW which were resolved by 7 May 2014.

The new system at Buckland Park has improved laboratory temperature stability and many more channels are being monitored with a new FPGA data acquisition system which allows small showers and one second counts to be monitored as well as the various directional beams.

Acknowledgements

We have appreciated the interest ion HEAMS by the Moscow neutron monitor IZMIRAN group. We have had support and interest from IPAS at the University of Adelaide and KACST in Riyadh, Saudi Arabia.