A Cosmic Ray Muon Detector for Astronomy Teaching

R.W. Clay[(1)], Z. Kurban[(1,2)], A.H. Maghrabi[(1,3)], N.R. Wild[(1)]

(1) Department of Physics and Mathematical Physics, University of Adelaide, SA 5005.

(E-mail: rclay@physics.adelaide.edu.au)

(2) Kashgar Teachers' University, Kashgar 844000, Xinjiang Uighur Autonomous Region, P.R. China.

(3) KACST, IAGR, Riyadh, 11442, Saudi Arabia.

Keywords: cosmic rays - teaching- Sun: solar-terrestrial relations

Abstract

Practical astronomy is usually taught using optical telescopes or, more rarely, radio telescopes. For a similar cost, complementary studies may be made of astrophysical particles through the use of a modestly sized muon detector. Such a detector records the arrival of cosmic ray particles which have traversed the heliosphere and the rate of muon detections reflects the flux of those particles. That flux is controlled by the day to day properties of the heliosphere which is in a state of constant change as the outflowing solar wind is affected by solar activity. As a consequence, a laboratory muon detector, whose count rate depends on the state of the heliosphere, can be an interesting and useful teaching tool which is complementary to optical or radio studies of the Sun.

1. Introduction

Practical teaching in astronomy usually concentrates on the use of optical telescopes. Occasionally, radio telescopes are used (e.g. Storey and Lloyd 1993, Storey et al. 1994) but practical considerations have usually precluded most teachers from delving into other areas of observational astronomy. By contrast, a large fraction of professional observational astrophysics deals either with photons in other energy ranges (such as x-rays and gamma-rays) for which the emission processes are often related to cosmic rays or with particle astrophysics directly. Cross connections through the body of astrophysics are then easily missed by students. Further, students often have limited time for observations and often fail to recognise that astrophysical objects can exhibit time variations and that those variations can be episodic and violent.

We have found that, for a cost comparable with that of a modest teaching telescope, it is possible to build a cosmic ray muon detector which allows students both to directly study an aspect of particle astrophysics and to see that our own Sun exhibits aperiodic and violent phenomena. They can also see that those phenomena are related to observational optical and radio astronomy and that they have geophysical consequences.

We were led to this work by our background in cosmic ray techniques and by a need to develop modestly priced equipment for student project work at levels from short high school projects through projects at all undergraduate levels to Masters research. The simple muon detection and recording system described below has proved to be understandable to students and, through its continual time variations, to be of continuing interest.

2. Cosmic Ray Muons

The vast majority of cosmic ray particles in space are charged nuclei. Their composition is dominated by hydrogen nuclei (protons) and their overall nuclear abundances are rather similar to the universal abundances found in nature. The exception to this is that some nuclei (Li, Be, B) are found in excess in cosmic rays as a result of the break up (spallation) of cosmic ray particles in their multi-million year passage to us. Such cosmic rays may reach the upper layers of our atmosphere where they interact with atmospheric nuclei. Those interactions, like most high energy particle interactions, produce pions and many of those pions decay to muons which then penetrate the atmosphere. Background material on this and other cosmic ray physics at an undergraduate level can be found in Clay and Dawson (1997).

Those primary interaction processes occur high in the atmosphere but the resulting secondary muons interact little with the intervening atmosphere except through a progressive loss of energy by ionisation. Thus, many reach ground level where they can be detected. These muons represent about half of the radiation burden of our bodies at sea level.

Due to the steep energy spectrum of cosmic ray particles, the majority of the muons which are detectable at ground level result from the interactions of rather low energy cosmic ray particles with our atmosphere. Those particles, with energies in the GeV range, can be severely affected by heliospheric magnetic fields and their intensity at the Earth reflects the state of the variable heliospheric plasma. In turn, the intensity of the muons at ground level is thus modulated by the state of the heliosphere.

3. A Simple Muon Detector

Many teaching laboratories have exercises in which students record cosmic ray muons with a simple geiger counter and use the resulting counts as an exercise (often tedious) to examine the properties of the poisson distribution. Geiger counters have too small a collecting area for astrophysical studies in which we need a sufficient count rate to be able to study intensity variations at the level of a fraction of a per cent above the statistical noise due to the poisson process. However, the principle of a laboratory muon detector for astrophysics is still very simple and uses some of the counting concepts of the geiger counter experiment in which each pulse is treated equally and is assumed to result from the passage of a muon.

The muons are detected by detecting the brief flash of light which they produce when passing through a piece of plastic scintillator. Such scintillator is commonly used in large quantities in high energy physics laboratories and is cheap compared with sodium iodide which is required for gamma-ray studies. We have purchased scintillator from common high energy physics suppliers but we have also been given surplus material from such laboratories. For the purpose of this experiment, the scintillator can be rather old and somewhat yellowed and still perform perfectly well even though it may be regarded as unsuitable for high energy physics. The light from the scintillator is detected using a photomultiplier tube. Again, most conventional tube types are adequate for this purpose.

The only serious limitation on the apparatus is that a sufficient rate of muons must be detectable. This means that, with a sea level flux of about one muon per square centimeter per minute, a scintillator area of the order of one square meter is required. This is in order that poisson statistical uncertainties (the square root of the number of counts) permit intensity variations of a fraction of a per cent to be resolvable in a few minutes of recording. Such a size of scintillator is best viewed by a photomultiplier with a diameter of at least 75mm (we use a common laboratory size of 120mm) from a distance of at least 600mm. The whole detector must be made light-tight (and photomultipliers are sensitive to the smallest of light leaks) so we enclose the scintillator/photomultiplier combination in a sealed wooden or galvanised steel box which is either roughly cubic or pyramidal with the photomultiplier at the apex.

If the enclosure is light-tight, the photomultiplier output will consist of a series of pulses, each one representing the passage of a muon through the scintillator. These pulses can be detected (after preamplification or not as one prefers) using a discriminator. This is a circuit, often found in university nuclear physics laboratories, which produces a standard logic pulse when an input signal, such as the pulse from the photomultiplier, exceeds a preset voltage (or current) level. We vary the photomultiplier gain with its high voltage adjustment to set the count rate from the discriminator to correspond to the expected muon rate i.e. about 150 counts per second for a one square metre scintillator. The experiment consists of counting these logic pulses over predetermined periods of time such as a quarter of an hour and observing how those numbers vary over periods of days or longer.

4. Muon Observations

The rate of muon detections depends on a number of factors, all of which can be used as a basis for student study. The photomultiplier/scintillator combination may well have a temperature dependence and a correlation of the rate of muon detection with the laboratory temperature can be of interest. In professional studies, this is a very serious issue but our experience has been that, for student work, astrophysical studies can go on independent of this concern. A more serious problem is the dependence of the detection rate on atmospheric pressure. Pressure data are usually available on the World Wide Web from a local

Meteorological Bureau or can be recorded *in situ.* In any case, a pressure correction of the order of 0.2%/mbar must be made. The reason for the dependence is simple. Since our atmosphere acts as an absorber for the muons, a period of high pressure is associated with more absorber above the detector and a lower detection rate results. An example of this effect for data collected over a period of several days is shown in figure 1. In this figure are shown: the raw muon count per 900s averaged over successive one hour periods, the variation of the atmospheric pressure, and a corrected counting rate assuming a 0.2% per millibar negative pressure coefficient. We have found the determination of the pressure/rate correlation to be interesting to students, as is the observation (visible in this figure) that the pressure has a two cycle per day variation, contrary to their expectation of one per day.

Once corrections for the local pressure and (possibly) the laboratory temperature have been made, resulting variations in count rate reflect the state of the heliosphere and the solar wind which determines (modulates) the intensity of the low energy cosmic rays which will later produce muons in the atmosphere. The cosmic ray particles pass inwards through the heliosphere against outward forces due to the outflowing solar wind, its associated plasma and trapped magnetic field. This results in a reduction in low energy cosmic ray intensity when compared with the interstellar intensity.

There is a long-term intensity variation over the solar cycle and over weeks or months which reflects overall solar activity and can be correlated with parameters such a sunspot number and the overall heliospheric structure (e.g. Hall et al. 1994 and references therein). There are also daily variations, visible in the early part of figure 1, due to the daily rotation of the Earth which allows the detector to successively view regions of greater and lesser cosmic ray density. However, the effects which are most rewarding to observe in project work are the rapid, short term, variations known as Forbush decreases (e.g. Nagashima et al. 1992 and references therein) which result from solar flare and coronal mass ejection activity. A one square metre detector is perfectly capable of recording those events. Figure 2 shows data taken by our muon detector for a Forbush decrease in January 1999. The rapid intensity decrease on 23 January is followed by a characteristic extended recovery. Data from sites on the World Wide Web confirm that strong solar activity was associated with the origin of this event, which was also seen by other radiation detectors around the world.

5. Other Heliospheric Data

Muon detectors are not usually the cosmic ray detectors of choice in the cosmic ray heliosphere community, neutron monitors are often preferred. Neutron monitors respond to lower energy cosmic rays which suffer more heliospheric modulation. However, neutron monitors do respond to the same fundamental phenomena as muon detectors and their (lower energy) data can be readily compared to the complementary muon data recorded by students. At least two neutron monitors have their data available in real time on the world wide web (see below) and real time correlations can be made between those and the muon data.

Since the root cause of rapid changes in cosmic ray intensity is solar activity which disrupts the solar wind, rapid changes in muon intensity usually occur some time, of the order of days, after a violent solar event. At that time, solar plasma has propagated to the vicinity of the Earth. The site of the solar event is often observable on the visible side of the Sun and can usually be found in sunspot or visual solar flare data, often occurring close to the foot of the solar magnetic field spiral which joins the Earth to the solar disk. That event will also cause solar radio activity. A further, direct, consequence of such events and their effect on the solar wind, is changes to the state of our magnetosphere with consequent effects on the magnetic field of the Earth. Those effects can be seen in the various heliospheric and terrestrial magnetic indices which are also available on the World Wide Web (see below) and can be examined by students.

6. Conclusions

A simple cosmic ray muon detector can be constructed within the resources of a university teaching laboratory which will enable students to study aspects of particle astrophysics and enable them to develop a more complete picture of the physical properties of the heliosphere. They rapidly recognise that our Sun, often regarded by them as benign and constant, can exhibit extreme violence and rapid variability.

7. Some World Wide Web Sources of Information

Data complementary to observations using the muon detector, or useful as an alternative source of teaching material, can be found at the following sites:

1. Daily records of cosmic ray (neutron monitor) intensity data are available at: http://odysseus/uchicago.edu/NeutronMonitor/neutron_mon.html

2. Real time neutron monitor data are available at: http://helios.izmiran.rssi.ru/cosray/main.htm and http://pgi.kolasc.net.ru/CosmicRay/

3. Useful solar and heliospheric data are available at: http://www.ngdc.noaa.gov/stp/SOLAR/sgdintro.html

4. An extensive discussion of the use of cosmic ray studies in undergraduate teaching and real time data from our muon detector can be found through the muon detector section of: http://physics.adelaide.edu.au/astrophysics/index.html

References

Clay, R.W. & Dawson, B.R., 1997, Cosmic Bullets, Allen and Unwin, Sydney

Hall, D.L., Humble, & Duldig, M.L., 1994, PASA, 11, 2, 170

Nagashima, K., Fujimoto, K., Sakakibara, S., Morishita, I., & Tatsuoka, R., 1992, Planet Space Sci., 40, 1109

Storey, J.W.V. & Lloyd, J.P., 1993, PASA, 10, 3, 225

Storey, J.W.V., Ashley, M.C.B., Naray, M., & Lloyd, J.P., 1994, Am. J. Phys., 62, 1077

Figures

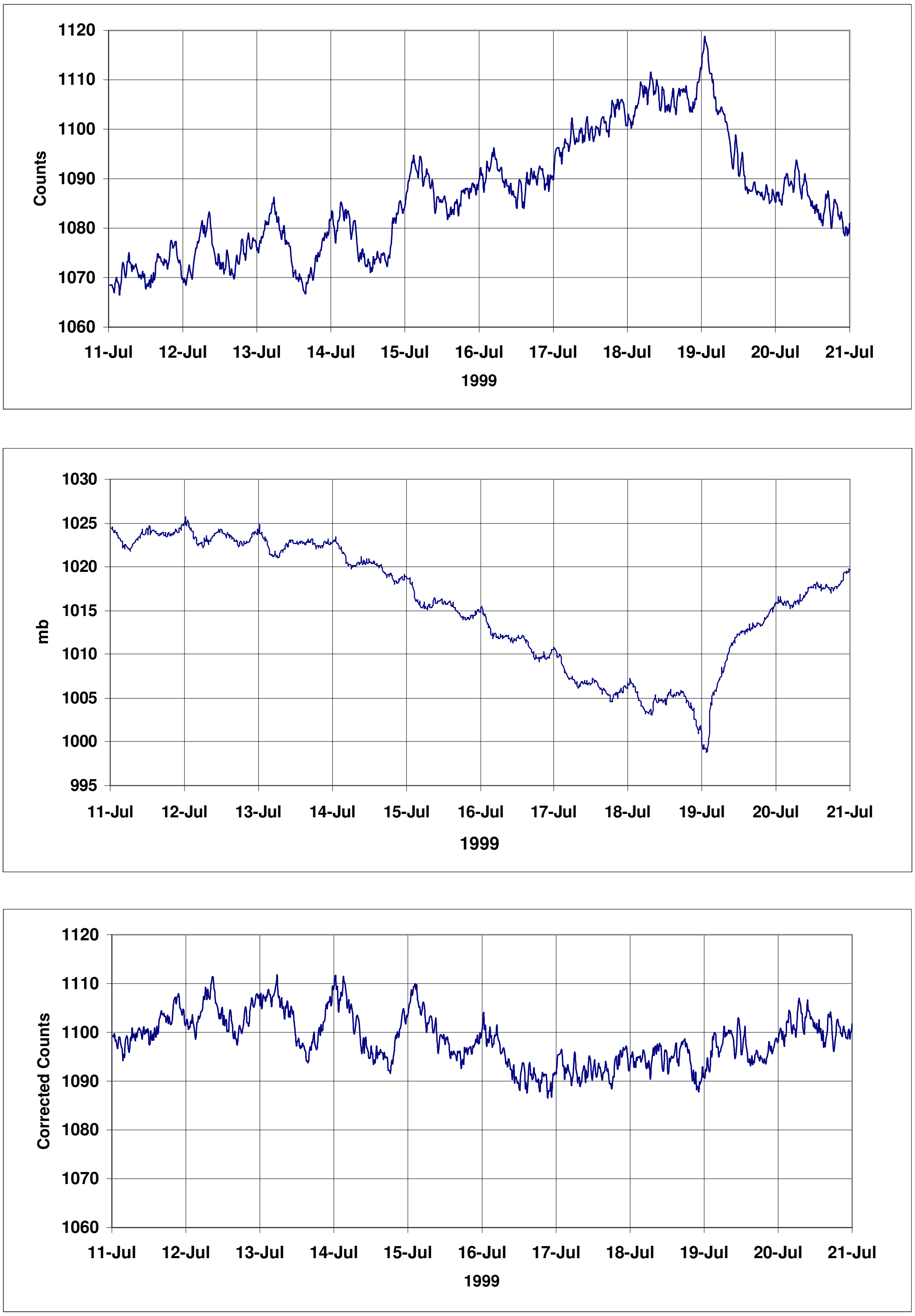
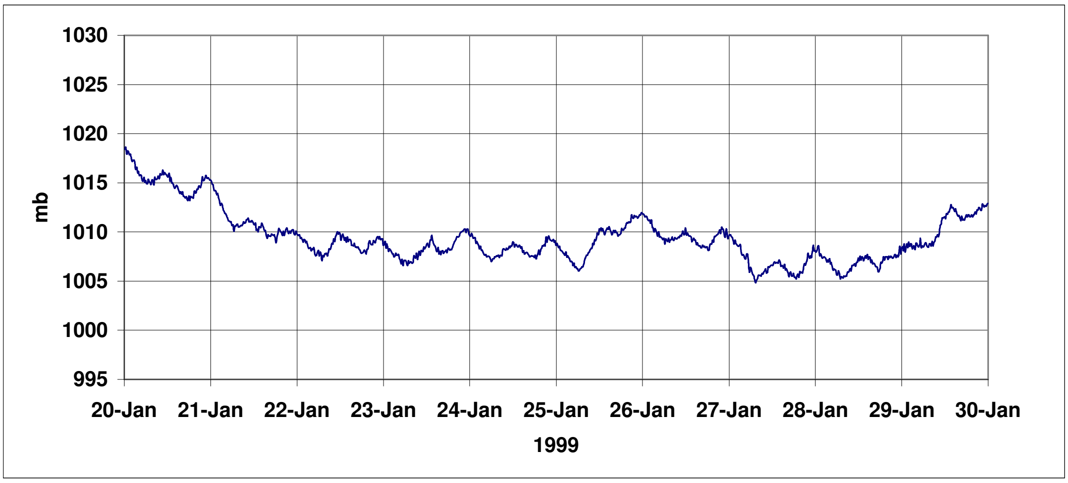


Figure 1- The time variation of the raw muon count data (divided by 100 for 900 s intervals) from our one square metre muon detector, the corresponding variation of the atmospheric pressure and the pressure corrected muon count data assuming a 0.2% per millibar negative pressure coefficient.



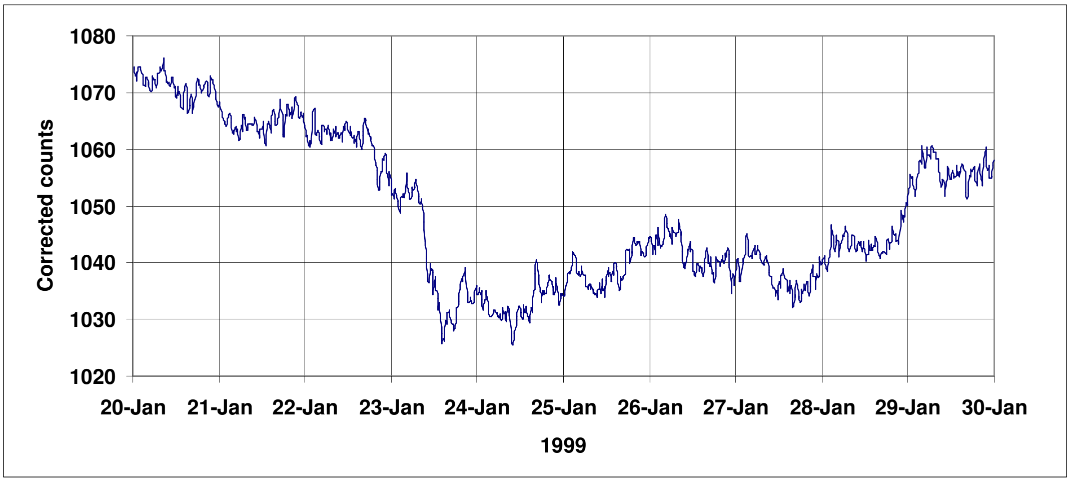


Figure 2- The time variation of the muon count rate, the pressure variation and the corrected rate as in figure 1 through a period of time which includes a Forbush decrease on 23 January 1999.