Cosmic Ray Related Undergraduate Experiments

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We describe here comic ray experiments which we have used in our undergraduate laboratories. The experiments allow students to get a taste of modern astrophysics and experimental particle physics for a modest cost. We also describe some related experiments.

1 Introduction

Primary cosmic rays are particles with very high energies whose origins in the cosmos are still largely unknown. They consist mainly of energetic nuclei although there are components of electrons, positrons and gamma-rays. There is also presumed to be a high energy neutrino component. All these components of the cosmic ray beam are currently subject to intense study and the field of cosmic ray physics in its many forms has been enjoying a resurgence in recent times (see the magazine articles listed later).

When high energy cosmic rays arrive at our atmosphere, they interact with atmospheric nuclei and produce cascades of particles which are known as cosmic ray showers or extensive air showers (EAS). Many of these secondary air shower particles reach ground level and contribute to the natural radiation background. They are quite plentiful and can be usefully studied in the undergraduate laboratory for the insight they give into particle physics processes and techniques and also into the astrophysics of their origin and propagation.

We describe here some straightforward experiments which we have used in undergraduate laboratory teaching and indicate some of the physics behind the experiments.

2 Cosmic Ray Astrophysics

In the main, cosmic rays are charged nuclei which travel to us through large cosmic distances both within our galaxy and in intergalactic space. The energies of these particles are huge. The detectable cosmic rays begin at energies of about 1 GeV (below which the outward flow of the solar wind is too strong to allow them to penetrate the heliosphere). The highest energy cosmic ray so far detected had an energy of 51J - a macroscopic energy carried by a microscopic particle. Between these extremes, the spectrum is remarkably close to a featureless power law relating flux to energy. There is a detectable steepening at a little below 10^{16}eV and a flattening above 10^{18}eV. The overall differential energy spectrum (intensity in a given energy interval versus energy) has a power law structure with an exponent a little less negative than -3. The power law form is believed to result from cosmic ray acceleration processes involving progressive acceleration in magnetic fields such as are found in supernova shells or other astrophysical shocks. The usual interpretation of the steepening is that it occurs when the gyro radius of the cosmic rays in the galactic magnetic field exceeds the thickness of the galactic disk (a few hundred light years) and the flattening is interpreted as the start of domination by a flux of extra-galactic particles. Typical galactic magnetic fields have a strong random component as well as an ordered component along the directions of the spiral arms. In strength, they are of the order of 10^{-10}T and fields between galaxies in galactic clusters may well be of the same order. As a result, with propagation times in millions of years (measured by the relative abundances of various long-lived isotopes), primary cosmic rays reach us with a randomised directional distribution which is close to uniform and featureless. Deviations from uniformity (anisotropies) are typically below 1%. That is, the brightest part of the sky is rarely over 1% more intense than the faintest.

Possible sources of cosmic rays must have physical properties such that the increasingly energetic particles are confined to the source region as they are accelerated and such that the acceleration process is faster than any energy loss mechanisms such as synchrotron radiation or interactions with the photons in space. At the highest cosmic ray energies, those photons are the very numerous low energy photons of the 2.7K microwave background. In considering possible sources, the need for containment and rapid acceleration force one to examine the magnetic fields of astrophysical objects and the detailed ways in which they can accelerate particles[1]. Magnetic fields associated with shock regions are thought to be likely acceleration vehicles and popular acceleration sites are supernova remnants for particles up to medium cosmic ray energies and hot spots in galactic (possibly Active Galactic Nuclei) jets up to the highest cosmic ray energies.

2.1 Propagation Calculations

It is interesting for more advanced students to follow possible cosmic ray trajectories in magnetic fields such as there are in our galaxy. We have done this with third year undergraduate students using PC's. The physics is straightforward. We assume that the propagating particles are protons, determine the particle direction and three components of the local magnetic field and derive the change in momentum over a distance step (which could be as much as a parsec (about three light years) for the higher energy particles). This gives the new velocity components (remember that the particles are highly relativistic so speed is not a variable) after a displacement which can be calculated using the pre-step velocity (or a more sophisticated average value). This process is iterated whilst the particle remains in the galactic volume. We usually encourage students to check that their program produces a circular trajectory whilst in a uniform magnetic field perpendicular to the velocity vector and that the radius of gyration is correct. A simple rule of thumb is that the radius of gyration should be 1kpc for 10^{18}eV protons in a 1μG (10^{-10}T) magnetic field. There are many possible magnetic fields which can be used as approximations to the galactic field. References to these can be found in papers such as Lee and Clay[2] and Lampard *et al.*[3]. A simple trick for determining the possible source directions for observed particles is to reverse the trajectories (assume that the particles are anti-protons) using the Earth as the particle source.

An alternative strategy, which is interesting to study in the context of the propagation of low energy particles through the Earth's magnetic field, is described by French *et al.*[4] who use numerical methods to derive trajectories from the integration of the equation of motion of a charged particle in a magnetic field.

3 Cosmic Ray Showers

The flux of cosmic rays falls steeply with energy (a steep power law as we just noted) and, at all but the lowest energies, direct detection in space is prohibitively expensive. Few direct data are available above 10^{14}eV. At higher energies, we are fortunate that the cosmic rays interact with the atmosphere of the Earth and produce cascades of secondary particles such that many particles are produced from a single primary particle. Those secondary particles deviate from the track of the primary particle due either to their momentum distributions in the center of mass or due to coulomb scattering with atmospheric charged particles. Such cascades are known as cosmic ray showers or (due to their lateral spreading) extensive air showers (EAS) (see e.g. Allan[5]).

Cosmic ray showers are initiated by a single high energy cosmic ray particle which interacts with an atmospheric nucleus (the interaction mean free path is typically a few percent of the total atmospheric material). This interaction characteristically produces pions whose mass energy comes from the kinetic energy of the initiating particle. The charged pions may interact again but many will decay to muons which then only interact through ionisation and often continue to the surface of the earth (and below) with no further catastrophic interaction. The neutral pions decay almost instantaneously into pairs of gamma-rays which, in turn, initiate elctromagnetic cascades which develop through pair production to produce electrons (and positrons) followed by electron bremsstrahlung to produce a further generation of gamma-rays. The electromagnetic cascades develop only until cascade energy losses become dominant (photoelectric and ionisation losses) and they then die out. The end result is that superimposed electromagnetic cascades are initiated along the track of the initiating particle (which only loses a fraction of its energy at each interaction) and the total particle number (mainly electrons, positrons and gamma-rays) builds to a maximum and then decays. The jargon is that the shower reaches shower maximum with a certain number of particles which is closely proportional to the primary (particle) energy (the rough conversion factor is 10^{10} to convert particle numbers at shower maximum to primary energy in electron volts). The decay in electromagnetic particle numbers past maximum is roughly exponential with an attenuation length of about 200g.cm^{-2}. The total vertical atmospheric depth is close to 1000g.cm^{-2} at sea level.

At ground level, then, there are three components: 1. the muons which are quite penetrating and originate high in the atmosphere; 2. the electromagnetic component (electrons/positrons and gamma-rays); and 3. a narrow core of "nuclear active" particles directly associated with continuing interactions of the central cosmic ray particle which may still be losing energy to pions etc. There are almost as many positrons as electrons (some are lost through annihilation in flight with atmospheric electrons) but most measurements such as we will describe do not discriminate between the two.

The primary spectrum is steep and many muons are produced by quite low energy primary particles whose electromagnetic components die out high in the atmosphere. The result is that there is a large ground level flux of so called "unaccompanied muons". Their flux at sea level (over all directions) is about one per square centimetre per minute and they present us with a convenient source of particles for laboratory measurements as well as contributing almost half of the natural sea-level background radiation.

4 Cosmic Ray Detection

Early cosmic ray studies depended on recording the ionisation within the volume of an electrometer (like a gold leaf electroscope) which caused the progressive discharge of the electrometer. (For an interesting discussion of early cosmic ray history, see the paper by Xu and Brown[6].). The geiger counter and the cloud chamber then became the workhorses of cosmic ray physics. For demonstration purposes, continuously sensitive diffusion cloud chambers can be built using dry ice to supersaturate air with a vapour but we have seen few useful measurements using such a device in undergraduate laboratories. Geiger counters or ionisation chambers are rather more practical but teaching instruments of this type generally have a low count rate due to their limited sensitive area. In the teaching laboratory they are used mainly to detect unaccompanied muons, possibly as examples of the coincidence technique to measure the angular distribution of the flux away from the direction of the zenith, or as the basis for the study of Poisson statistics. (See for example Gould and Ives[7].). These devices are rather slow which results in a significant problem with accidental coincidences and an inability to exploit fast timing techniques. A preferred technique which has been available for almost half a century is the use of scintillation detectors.

These detectors consist of a slab of transparent plastic which is chemically doped to emit scintillation light following the passage of a charged particle. Typical sizes used for cosmic ray work are of the order of 500mmx500mmx50mm although there is great variation. The emitted light is detected using a photomultiplier tube whose output goes to electronic equipment of types which we will discuss later. A simple cosmic ray detection system which could be used for the experiments below might consist of two scintillator/photomultiplier combinations for a cost of \$5k to \$10k. The photomultiplier and the scintillator would be contained in a light tight enclosure of some type (we use simple pyramids made from sheet steel, with the tube at the apex, painted white inside except the top side of the scintillator, and with the component parts of the pyramids sealed with two layers of black cloth tape). Detector elements such as these are commonly used in accelerator laboratories and from time to time become available from research groups at those labs. We have occasionally received such equipment at a nominal cost from experimental groups of this type, thus reducing the cost of teaching undergraduate particle physics through cosmic ray studies to very modest levels.

Photomultipliers may be more readily available than large pieces of scintillator. For instance, we have acquired tubes which have become surplus to gamma cameras in local hospitals. In this case, muon detectors can be built simply by putting the tube face in contact with a substantial piece of glass. Many cosmic ray muons travel faster than the local speed of light in the glass (and the glass faceplate of the tube) (c divided by the refractive index of the glass) and Cerenkov light is emitted. This is not so intense as scintillation light and a single particle peak (see below) will not be resolved unless some form of gating is employed. However, particles will be readily detected and the interesting directional properties of Cerenkov light can be observed. The light is emitted from each incremental path length in a forward direction (scintillation light loses directional information) in a cone with a half angle whose cosine is given by the reciprocal of the refractive index of the glass[8].

5 Single Particle Detection and Muon Absorption

A very simple undergraduate experiment can be carried out with a single detector arranged with the scintillator horizontal and the photomultiplier below. A detector such as this, which requires no coincidence with a second detector, will overwhelmingly record single unaccompanied muons which pass through the detector and only lose energy by ionisation. Their energy loss rate will be about $2\text{MeV}(\text{g.cm}^{-2})^{-1}$ (this would be an approximation to the dE/dx for ionisation loss such as discussed by the Particle Data Group[9]). Since the muons tend to come from a roughly vertical direction, they will all tend to pass through similar amounts of detector material (this increases only slowly as the secant of the direction from the vertical) and deposit similar quantities of energy. The signals from these muon events are thus all rather similar in magnitude. A multichannel analyser will record the spectrum of deposited energies for these events as a broad peak corresponding to the average energy deposition. This is often known as the "single particle peak".

If the spectrum is recorded for an extended period of time, it will be seen to extend to very high values of energy deposition, many hundreds of times the single particle value is possible. This is due to the passage of multiple particles through the detector as a shower front passes. One can interpret a particular pulse height in terms of particle numbers measured in terms of the single particle peak and the particle density is then expressed in terms of "vertical equivalent muons". This is conventional practice even though it is recognised that the majority of the multiple particles are electrons, positrons and gamma-rays each of which deposit an energy only loosely related to the ionisation energy deposition of a muon. This extended spectrum (frequency of deposition of a certain energy versus energy but expressed in numbers of particles) is known as the density spectrum and it can readily be drawn as an integral (total counts above a given level) spectrum on log-log axes. It is a clear power law with a break to a steeper power law at a density of several hundred particles per square metre. This spectrum is closely related to the cosmic ray energy spectrum (and the steepening is probably related to the energy spectrum steepening close to 10^{16}eV) since the total number of particles in a shower reflects the primary energy and also determines the particle density at the detector. However, apart from mirroring the structure of the primary particle energy spectrum, the density spectrum itself is enigmatic and its interpretation has been quite controversial[10,11].

With scintillator more than 20mm thick, the single particle peak is usually comfortably resolved from the system noise and the signal amplitude of the peak can be taken to correspond to the mean signal from a vertical muon. This is not quite obvious and results from the rough cancellation of two effects, the path length distribution due to various zenith angles of incidence and the properties of the Landau distribution for the energy deposition[12]. A discriminator (an electronic circuit which produces an output pulse only when the input level exceeds a preset "discrimination" level) can be set at a level between the noise and the single particle peak to select single particles and their rate may be determined to be about one per square centimetre per minute for a detector in a horizontal plane.

The muons are continuously losing energy through ionisation and some will effectively lose all their remaining energy in their passage through further matter. As a result, the insertion of absorbing material above the detector will reduce the detection rate. This absorber may be layers of lead (of the order of centimetres for straightforward results), house bricks or, perhaps, a tank of water to give variable levels of absorption. Using different types of material, students can confirm that the appropriate units of absorber thickness are grams per square centimetre, roughly independent of the nature of the absorbing material. They can also determine an absorption coefficient in terms of percentage rate reduction per g.cm^2. We will use this later. Some lateral thoughts on such experiments are given by Jones[13] who discusses muon absorption through the various levels of a building and the background count rate at various altitudes: best studied above a layer of snow.

Some muons will lose sufficient energy to stop in the scintillator, particularly if it is large (maybe a substantial piece of NaI rather than plastic). These muons can be used to determine the muon lifetime although the experiment is not easy. The muon decays to give an electon which also produces a signal in the detector. The experiment then consists of using a well shielded detector with low intrinsic radioactivity and looking for signals which are time separated by less than about 20μs. These signals are distributed exponentially in time as a reult of the 2.2μs mean lifetime of the muon. The signal is more easily seen if the recording system is gated by external detectors arranged to trigger on the detection of a muon above the experiment without a corresponding muon below. There are some apparently straightforward experiments of this type described in the literature such as the one by Hall *et al.*[14] which requires only modest equipment. An awesome extension of that experiment is described by Amsler[15] and allows (perhaps advanced) students to study the muon magnetic moment.

6 Coincidences and the Decoherence Curve

The addition of a second cosmic ray detector makes a further significant number of experiments possible. This detector can also employ a discriminator set at the single particle level and students can determine a better muon rate measurement by placing this over the first (scintillators closely above each other with one detector inverted) and counting only when there are pulses from both detectors. This situation can be recognised with the use of an AND gate which has the signals from the two discriminators as its input signals. The circuit is then referred to as a coincidence circuit. The absorption measurement is also now better controlled since the absorber can be placed between the detectors (with a fixed detector spacing to avoid changes in solid angle - we place the upper detector on a trolley which can be wheeled over the lower detector).

If the detectors are now separated horizontally, it ceases to be possible to obtain coincidences with single muons and the detected coincidences are from related (but different) air shower particles. The particles in an air shower are all relativistic and travel at speeds close to that of light. The shower structure is thus like that of a saucer as the laterally scattered particles lag slightly behind the central "core" particles. This lag, and the time spread of the shower front, is only of the order of nanoseconds and so the coincidence resolving time need only be a few tens of nanoseconds (or a time a little above the system risetime whichever is longer).

It is instructive to determine the coincidence rate as a function of detector separation - the decoherence curve. This can be measured inside the laboratory out to distances of a few metres. The result is much steeper than the characteristic shower width of the Moliere radius (about 80m at sea level) associated with scattering of the electron component of the shower and demonstrates that the central shower core of "nuclear-active" particles has a steep lateral spread of only a few metres in dimension. Coincidence rates fall quickly with increasing spacing and overnight runs are convenient at the larger spacings.

Students can measure the time spacing between successive coincidences quite simply when the detector separation causes the rate to fall to a mean value of the order of one event per minute. The distribution of these time spacings is close to that expected of a random source and can readily be shown to follow the expected exponential distribution. In fact, the distribution deviates from exponential imperceptibly over orders of magnitude in probability. Students are often surprised to learn that the most probable time spacing for random events is zero and the mathematics to show that it is to be expected is not difficult.

7 Shower Absorption

The rate of coincidences may be measured as a function of absorber thickness as was the detection rate for single muons. In this case, the absorption coefficient is greater since the shower as a whole is less penetrating than individual muons (which eventually dominate the shower particle population at large atmospheric depths). The shower attenuation length (closely related to the attenuation coefficient) is a little below $200\mathrm{g.cm}^2$, about one fifth of that for the muons. We note thst this value depends on the siting of the experiment. The electromagnetic particles are affected by passage through substantial building materials and the shorter attenuation length is found under a light roof and with detector spacings (above a few metres) which will remove the detectors from the proximity of the shower core. These considerations do not apply particularly to muon measurements with single detectors.

8 Barometric Coefficients

The atmosphere is not an ideal absorber for a cosmic ray detection experiment since its properties change over quite short periods of time. Variations over an extended period of time with an amplitude of 30 millibars of pressure are common and that change in pressure corresponds to a change in atmospheric absorber depth of close to $30\mathrm{g.cm}^{-2}$. This can be a significant factor to be taken into account when measuring the absorption coefficient which we have just described and students should note the barometric pressure whilst carrying out those observations. Alternatively, the amount of absorber can be kept constant and both the rate and the pressure monitored as functions of time. This yields a barometric coefficient for either single muons or cosmic ray showers depending on which of the previous experimental arrangements is used. A logging counter is very convenient for this purpose as is a pressure detector with an accessible electronic output. Quite cheap pressure sensors are available for the latter purpose without the necessity of purchasing fully constructed instruments. We have used a LabView system for logging data such as this but other PC based data logging programs and interfaces are readily available and suitable since the data rate is low.

We record the total number of counts in 15 minute intervals and the variation with pressure is clear to even casual observation for the muon records. It is interesting for students to see the effect so clearly and also to see the twice daily cycle of the atmospheric pressure superimposed on the irregular pressure variations. This pressure is the dominating effect on the data but other effects are present. There is an effect due to temperature variations at high altitudes which affects the chances of pions interacting before they decay to muons but this is not a factor which can easily be corrected for. There is also an effect due to the occasional reduction in the low energy cosmic ray intensity at the Earth by increases in the solar wind at times of intense solar activity. Some of these “Forbush Decreases” are observable using a simple muon counter such as we have described. These are most easily seen if the counting rate is first normalised by correcting for the current atmospheric pressure using a predetermined barometric coefficient.

Again, the barometric coefficient is higher (typically of the order of $0.8\% millibar^{-1}$) for the coincidence measurements since it is the shower as a whole which is being attenuated and the attenuation length is much shorter than that of the muons - by a factor of about five for the soft component compared to the muons.

The barometric coefficient is related to the material absorption coefficient we discussed earlier but is not the same since the atmosphere is extended and muons have a finite lifetime. This gives the teacher an opportunity to discuss the muon lifetime and the interpretation of these barometric data which are related to those which confirmed the time dilation prediction of the special theory of relativity. A leader in those early measurements was Bruno Rossi and his autobiography[16] is most interesting in this context (p53). His early text on cosmic rays is also still useful for background understanding. An interesting undergraduate experiment reproducing the essence of that work is described by Easwar and MacIntire[17].

9 Muon Speeds

Provided that the photomultipliers used in the detectors are "fast", ie they have risetimes of a small number of nanoseconds (this is common with small, 25-50mm, tubes but quite expensive for larger tubes), there are interesting fast-timing experiments which are readily accessible to students. We take the (negative) signals direct from the two detector photomultipliers to discriminators which respond with an uncertainty in time limited by the 2-3ns of the scintillator/tube/discriminator combination. For timing purposes, the relative times of the discriminator outputs may be measured with standard time to digital converters but a good option is to use a modern digital oscilloscope such as those produced by Tektronix (the TDS family) which are available for a very reasonable cost. We have carried out these experiments with an instrument having 100MHz bandwidth and 500 mega samples per second rate. It is possible to carry out the following experiments without a really fast coincidence circuit and fast discriminators if the direct signals from the detectors are displayed on the oscilloscope screen as well as going to a modest coincidence system.

We trigger the oscilloscope externally with a coincidence pulse, whose timing is not critical. We then display the two discriminator pulses using the digital oscilloscope. The time difference between these pulses is what is required. This can be measured manually off the screen or, if the instrument has a maths option, one pulse can be deliberately delayed to ensure that it always arrives last, inverted and then added to the earlier pulse. The resulting maths signal is a pulse whose length equals the time difference between the input pulses. Tektronix software will measure that pulse width/time difference. Clearly, with 100MHz bandwidth, the instrumental uncertainties are important to the timing but the pulses are identical in shape for each coincidence so averaging gives a good overall measurement.

In order to measure the speed of muons, we carry out such a measurement first with the detectors immediately above each other and then after changing the vertical separation. The change in mean time differences between the pulses from the two detectors after one of them has been moved plus a measurement of the vertical displacement gives the speed (even over a displacement of less than a metre). This technique avoids the necessity of finding an absolute time difference through measurements of cable lengths etc. although it is instructive to show students the effect of a change in cable length. This allows them to derive the velocity factor for the cable (typically the signal speed is about 0.6c). Students can improve their muon speed result by progressively raising the upper detector to higher levels for further measurements. We have done this through four floors of a building although, as the displacement is increased, the solid angle and, thus, the rate reduces quite quickly.

If the detectorts are now placed side by side, there is still a substantial coincidence rate but this cannot be due to single muons traversing both detectors. It is due to different particles in the shower front being detected. The shower front is only a few nanoseconds thick and this thickness can be estimated by examining the spread in the timing data when the detectors are above each other and also when they are side by side. Both experiments include the same timing uncertainty but the side by side experiment has an additional timing spread due to the possible locations of the triggering particles within the shower front. Subtraction of the uncertainties (assumed to add in quadrature) will yield an estimate of the thickness of the front.

10 Muon and Shower Directions

Cosmic ray particles do not travel to us through the atmosphere only from the zenith. They arrive with a distribution of zenith angles[18] which results from their attenuation processes in the atmosphere. Muons have roughly a $\cos^2$ dependence on angle from the zenith and showers as a whole depend on a much narrower $\cos^{8-9}$ when an allowance has been made for solid angle effects. This reflects the different attenuation lengths of the muon and the electromagnetic (electrons and gamma-rays known colloquially as "the soft component") components. A traditional undergraduate cosmic ray experiment is to take two geiger counters in coincidence to define a muon arrival direction and thus to measure the rate of coincidences due to single muons as a function of zenith angle[7] . The mesasurement of the distribution for showers is more complex.

We can use the technique just described with the digital oscilloscope to measure interesting properties of the shower direction distribution. First, we have to ensure that the delayed pulse is sufficiently late that there will be no case in which the time ordering is reversed. The addition of a little more cable in that channel will be sufficient. The detectors are then spaced horizontally and the distribution of time differences found as a function of horizontal spacing. At this stage, all that are of interest are the mean and standard deviation of the distribution. As the spacing is increased, the mean stays constant but the standard deviation increases in proportion to the spacing. This is because the time difference between the detectors results from the shower front (plane to a good first approximation) sweeping across the detectors so the time difference reflects the time between the front passing first through one detector and then the other. This difference is proportional to the detector spacing for a given direction and so the spread in overall times (simply recorded by the standard deviation at each spacing) is also proportional to the spacing for a fixed distribution of zenith angles. The mean delay corresponds to the intrinsic time difference between the channels since the distribution is symmetrical. This is fixed for all spacings.

If the detector spacing is sufficient (in our case about 10m), the detailed time distribution can be examined. This reflects the relative likelihood of various arrival directions in zenith and azimuthal directions. The azimuthal distribution should be uniform since there is no preferred direction but the zenith distribution depends both on the increasing solid angle with angular distance from the zenith and on the attenuation of showers at higher zenith angles due to increased atmospheric paths. The latter is closely related to the coincidence attenuation and barometric coefficients which earlier experiments measured. The result of the time distribution measurement can be readily interpreted using Monte Carlo modelling techniques and a knowledge of the overall zenith angle distribution. One can predict, for instance, the number of events with time differences (from the mean) below 5ns and between 5ns and 10ns as indicated in table 1. This allows the student to use the shower attenuation length of about 180g.cm^{-2} to derive the exponent of the integral cosmic ray energy spectrum (or more correctly the exponent of the shower size spectrum).

11 Radioastronomy

Radioastronomy is intimately asociated with cosmic ray physics. It is used to determine the properties of the magnetic fields which deflect charged cosmic ray particles, the 21cm line is used to determine the structure of our galaxy and other galactic sources of cosmic rays and the synchrotron emission which is studied is a direct result of the existence of high energy cosmic ray electrons.

Modern radio astronomy uses expensive equipment, well beyond that accessible by undergraduate laboratories. However, modern electronics and the commercialisation of satellite communication has made possible interesting radio studies using inexpensive but sophisticated equipment. Storey et al. [19,20] have discussed the use of satellite equipment to study the 21cm line of atomic hydrogen from our galaxy using satellite technology. Since that time, the desire for cheap SETI systems has resulted in a further reduction in the cost of setting up an undergraduate radioastronomy programme. A cost of about $2000 will provide a useful dish, low noise front end, down converter and receiver (http://www.setileague.org/homepg.htm).

12 Solar Studies

Our Sun presents us with an invaluable laboratory for the study of high energy astrophysics. Solar flares are associted with the acceleration of high energy poarticles. The outward movement of solar plasma limits the observable cosmic rays to those with energies above 1GeV. That plasma, when emitted by a solar flare, results in the Forbush decreases which are observable as we indicated above.

The solar cycle can be studies through the observation of sunspots either through projection onto a white screen through one side of a pair of binoculars (with the focus wound out to its maximum) or through a small telescope (with care to limit the aperture to avoid burning the screen). An alternative is to use a commercial solar filter with a telescope and use it in accordance with the manufacturers instructions. STUDIES OF THE SUN REQUIRE PARTICULAR CAUTION WITH STUDENTS WHO MAY NOT BE EXPERIENCED WITH PROPER LABORATORY PRECAUTIONS. The sunspots will soon reveal the one month rotation period of the Sun and a strong sunspot group may be identified with the observation of a Forbush decrease.

13 Conclusions

Cosmic rays provide us with a beam of particles which can readily be investigated in the undergraduate laboratory. Those particles are of interest as they constitute a significant part of our total radiation exposure, because their origins are of considerable topical interest in astrophysics and because their measurable properties can introduce students to techniques relevant to current particle physics.

14 Some Useful Web Pages

Daily records of cosmic ray (neutron monitor) intensity data are available at:

http://odysseus/uchicago.edu/Neutron Monitor/neutron.

Useful cosmic ray related solar data and information are available at:

http://www.ngdc.noaa.gov/stp/SOLAR/sgdintro.html

The Web page of the Auger project contains useful background on the highest energy cosmic rays:

http://www-td-auger.fnal.gov:82/

A particularly useful Auger-related Web page is that in Paris:

http://www-lpnhep.in2p3.fr/auger/welcome.html

15 Background Material

There have been a number of articles and a book relating to cosmic ray physics which are readily accessible at an underground level.

Book

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Journal Articles

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Ratio	1.94	2.46	2.77	3.12
C	3	3.5	4	4.5
γ	2.2	2.4	2.6	2.8

Table 1: The relationship between the ratio of the number of recorded time differences (between detectors spaced by 10m) which are less than 5ns and which are between 5 and 10ns, the C factor of Ciampa and Clay[18], and the index of the power law integral cosmic ray energy spectrum (γ). A shower attenuation length of $180 g.cm^{-2}$ is assumed. In a recent experiment, we found a ratio of 2.2 with an uncertainty of 0.2.