HiSPARC

Carrying out particle physics research
through data collection and analysis

contents

This guide includes details on how to access and download HiSPARC data, how to get started with the project in school and other useful information such as guidance on statistical analysis and further sources of information. If you have any queries please contact the Institute for Research in Schools at info@researchinschools.org

Introduction

The High School Project on Astrophysics Research with Cosmics (HiSPARC) is an international project in the area of particle astrophysics that aims to take cutting-edge cosmic ray shower science into secondary schools.

HiSPARC involves schools across Europe in real scientific research. It was born more than a decade ago in the Netherlands, with ongoing participation of over one hundred schools. Relatively recently, HiSPARC has been introduced to the UK, with a network of schools forming mainly in the Midlands, West and South West of the country, as well as London and Sussex. Thanks to access to the entire HiSPARC database (this contains data from all of the detectors on the network) the project allows research-quality science to be performed in schools without the need for a detector on site.

The detector comprises a pair of scintillators and phototubes, and an Internet-connected analogue to digital converter and GPS unit that uploads data to a central database. Some schools host a detector on their school roof. All schools join the network and share their data, nationally and internationally.

Correlation of signals over a large area allows detection of giant air showers and other cosmic ray phenomena. These include:

■ the upper limit on the energy of cosmic rays from distant sources (Greisen–Zatsephin–Kuzmin limit),
■ detection of widely separated and nearly simultaneous events (Gerasimova-Zatsepin effect),
■ investigation of atmospheric influences, and triangulation of very high energy cosmic rays.

The research exploits links between particle physics, astrophysics and astroparticle physics. In the last few years a research conference has been held in which students researching cosmic rays meet to discuss their progress and results with fellow students and researchers.

For more information on the project please visit https://www.hisparc.nl/oud/en/

Professor Cristina Lazzeroni
Professor of Particle Physics
University of Birmingham

Institute for Research in Schools

The Institute for Research in Schools (IRIS) supports hundreds of schools in carrying out original science projects in collaboration with universities and research institutes. Since 2016 IRIS has delivered more than ten research collaboration projects across biology, chemistry, physics, engineering, environmental sciences and psychology.

Through participation in projects such as HiSPARC there are many benefits to students, teachers and technicians.

For students, participation can:

■ Improve knowledge and skills.
■ Improve attainment.
■ Increase uptake of STEM subjects at school and university.
■ Connect science studied at school to the real world.
■ Result in attendance at conferences and visits to research facilities.

For teacher and technicians, benefits include:

■ Reconnection to identity as a scientist.
■ Improves subject knowledge and skills.
■ New approach to professional learning.
■ Sense of satisfaction in making genuine contribution to real research in collaboration.
■ Opportunity to challenge students without curriculum and exam pressures.

To find out more about IRIS please visit www.researchinschools.org

This section summarises the most relevant sections of the curriculum in Scotland, England and Wales.

Scotland

Higher Physics:
■ Particles and waves: 　• The standard model 　• Forces on charged particles

Advanced Higher Physics
■ Electromagnetism: 　• Fields ■ Quanta and waves 　• Particles from Space: Cosmic rays 　• Particles from Space: Solar wind

England

AQA A-level Physics
■ Particles and radiation ■ Nuclear Physics

Edexcel A-level Physics
■ Nuclear and Particle Physics

| OCR |
| --- |
| ■ Nuclear and Particle Physics |

Wales

WJEC A-level Physics
■ Motion, Energy and Matter: particles and nuclear structure ■ Fields: electrostatic fields, magnetic fields

Other awards

There are opportunities for students to investigate cosmic rays within syllabuses at GCSE and National level in topics such as:
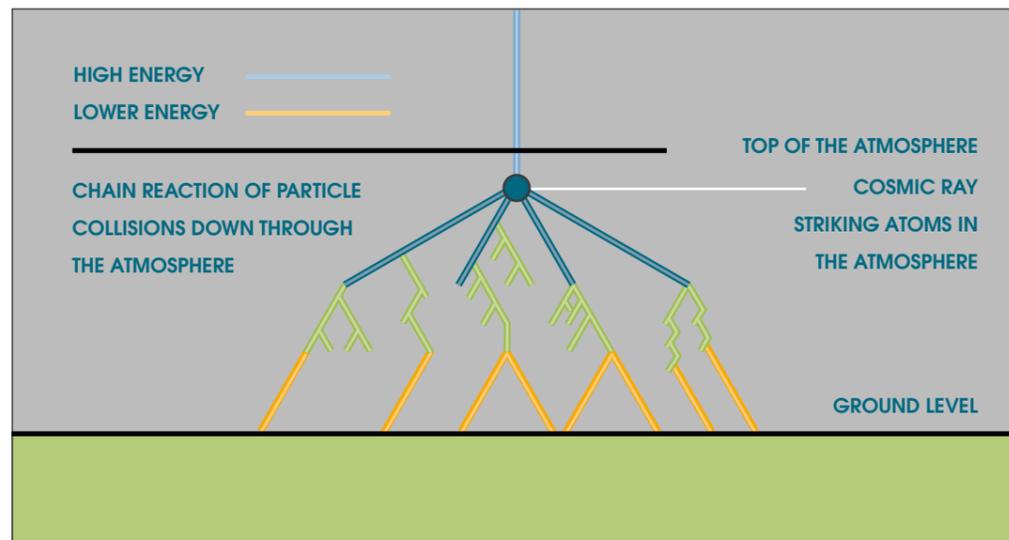
■ 'explain the sources of background ionising radiation from space'

Further opportunities to analyse data sets and develop data analysis skills sit within Maths and Computer Science courses.
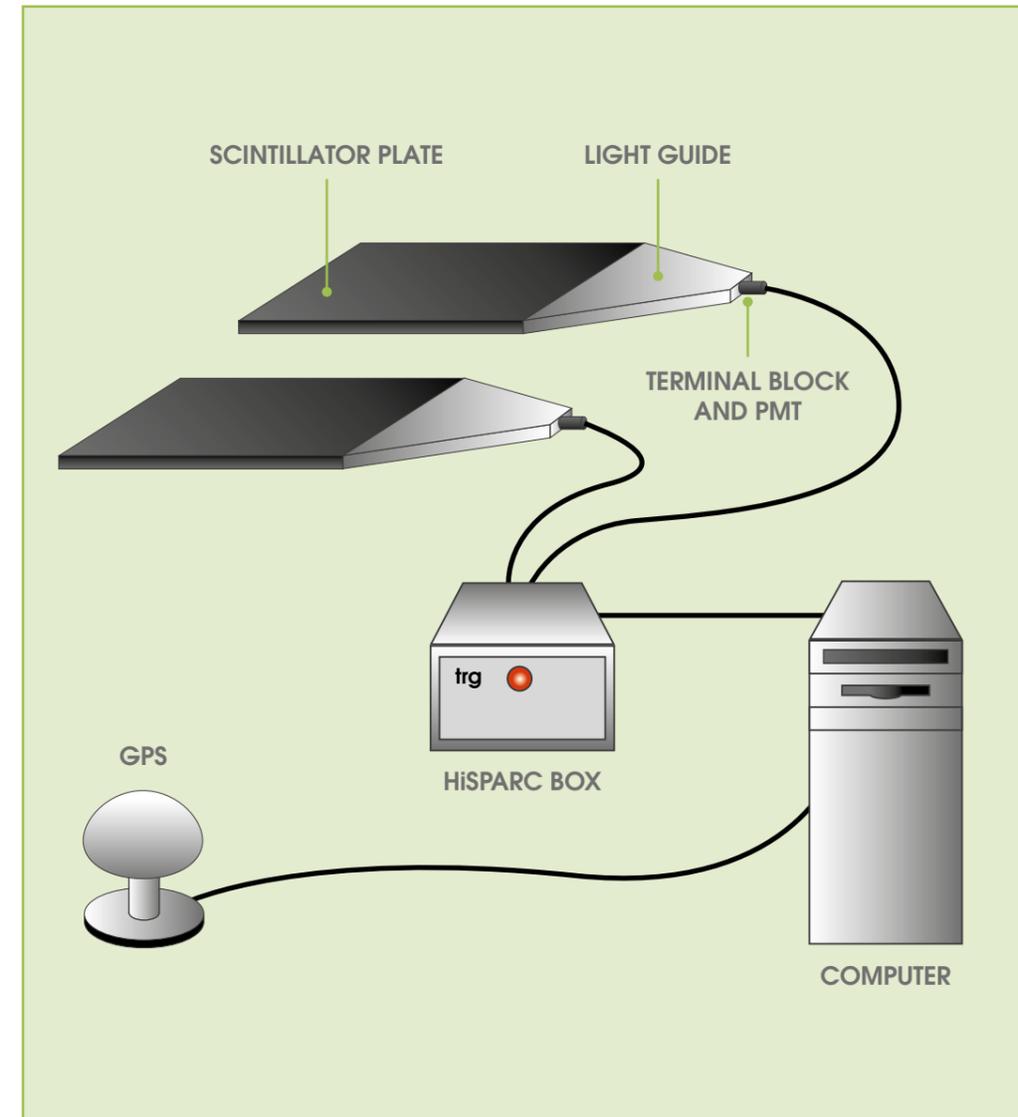
■ The HiSPARC detectors use scintillators to detect the charged particles that arise during collisions of high energy cosmic rays. If a charged particle travels through the scintillator material, this generates a flash of light. These light pulses are converted into electrical signals by photo multiplier tubes. These data is stored on a computer and uploaded to a central database.

■ For each individual cosmic ray event there are a large number of particles that reach the surface of the Earth. In order to identify whether the particles detected come from the same shower, the HiSPARC detector has two scintillator plates (each with an area of 0.5 m2, separated by several metres) and the particles detected at each plate must have the same arrival time.

Particles detected:	
Cosmic ray event (upper atmosphere)	Protons, Helium nuclei or other heavier nuclei.
Secondary rays	Pions, Kaons, Positrons, Muons and others.
Ground level	Electrons, muons, cerenkov radiation and neutrinos.

HIGH ENERGY

LOWER ENERGY

TOP OF THE ATMOSPHERE

CHAIN REACTION OF PARTICLE COLLISIONS DOWN THROUGH THE ATMOSPHERE

COSMIC RAY STRIKING ATOMS IN THE ATMOSPHERE

GROUND LEVEL

- Data from different detectors spread over a large area can be compared, allowing the exploration of the spread and reach of single cosmic ray event. It is possible to use the particle density and angle of arrival to find the energy of the original cosmic ray.

- For further information about the detector please see the articles listed in Appendix A.

- If you are interested in buying and installing a HiSPARC detector, please contact the University nearest to you who works on HiSPARC – their details are listed below:

Institute of Physics	Chris Shepherd	Chris.Shepherd@iop.org
University of Bath	Dr Alessandro Narduzzo	a.narduzzo@bath.ac.uk
University of Birmingham	Cristina Lazzeroni	C.Lazzeroni@bham.ac.uk
University of Bristol	Jaap Velthuis	Jaap.Velthuis@bristol.ac.uk
University of Cardiff	Paul Roche	paul.roche@astro.cf.ac.uk
University of Sussex	Fabrizio Salvatore	P.F.Salvatore@suss ex.ac.uk

Literature review task 4

Before beginning analysis of the HiSPARC data, students should complete a literature review. Guidance on how to approach this task can be found online at the IRIS website.

There are a range of articles covering background information relevant to HiSPARC. A full list of these can be found in Appendix A. The purpose of this task is to encourage students to develop their knowledge of the field so that when it comes to the analysis they have a good understanding of the context of the results.

The topics covered within the articles include:

Cosmic rays:
- What are they and where do they come from?
- How much energy do they possess and how do they obtain it?
- What happens to cosmic rays when they enter the Earth's atmosphere?

Detector technology:
- What is a scintillator and how does it work?
- What is a photomultiplier tube and how does it work?
- How could you reproduce the direction of the cosmic ray particle?

Scientific research:
- What are the basic steps when doing scientific research?
- Is it necessary to formulate a hypothesis before you start your research?
- Is it necessary to do the same research multiple times?

The CERN@school and TimPix projects from IRIS will also provide relevant background information. These resources can be downloaded from the IRIS website.

5   Analysing Data
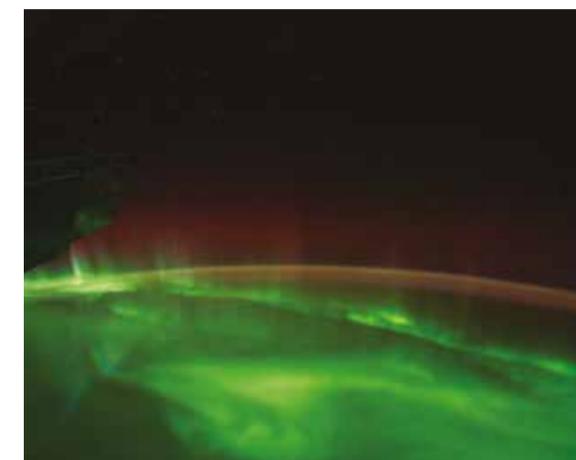
This section details how to access data from HiSPARC detectors and provides suggested starting points for investigation.

Downloading data

- The HiSPARC public database can be accessed via: https://data.hisparc.nl/show/stations_by_country/

- This site gives access to all HiSPARC stations, their names, codes and locations as well as information on how the station operates.

- You can download event data down to the millisecond from the data download section of the site and entering your own search criteria: http://data.hisparc.nl/data/download/

- The Dutch team have developed a Python framework called SAPPHiRE which provides functionality to analyse the HiSPARC data. It also contains a module to download data from the Public database: https://pypi.org/project/hisparc-sapphire/

- Some schools have written their own Python programmes to access the data
.

Data available

The HiSPARC detectors collect a range of different measurements. You don't necessarily need all of these fields. For a simple approach you can download the bin number and number of events. The full list of available fields include:

- date: time of event (GPS calendar date)
- time: time of event (GPS time of day)
- timestamp: time of event (UNIX timestamp)
- nanoseconds: time of event (number of nanoseconds after timestamp)
- pulseheights (4x): maximum signal pulseheight (ADC)
- integral (4x): integral of the signal (ADC.ns)
- number_of_mips (4x): estimate for the number of particles in the detector
- arrival_times (4x): relative time of arrival of the first particle in the detector (ns)
- trigger_time: relative time of the trigger timestamp (ns)
- zenith: reconstructed shower axis zenith angle (deg)
- azimuth: reconstructed shower axis azimuth angle (deg)

Further information about the data available can be found here: https://www.hisparc.nl/oud/en/hisparc-data/

Background information articles

Introduction

- Introduction to HiSparc

Core articles

- "The Sun" by N.G. Schultheiss
- "Solar Winds" by N.G. Schultheiss
- "Introduction Cosmic Radiation" by N.G. Schultheiss
- "Early Research into Cosmic Radiation" by J. Kortland
- "Sources of Cosmic Radiation" by J. Kortland
- "Elementary Particles" by Koos Kortland
- "Muon Decay" by Koos Kortland
- "Air Showers" by Koos Kortland
- "Collisions inside Air Showers" by N.G. Schultheiss

Extension articles

- "Stellar Evolution" by J. Kortland
- "van der Waals & Wilson" by N.G. Schultheiss
- "Compton" by N.G. Schultheiss
- "Cherenkov" by N.G. Schultheiss
- "Standard Model – Particles" by N.G. Schultheiss
- "Standard Model – Forces" by N.G. Schultheiss

Further reading articles

- "Collisions" by N.G. Schultheiss
- "Michelson & Morley" by N.G. Schultheiss
- "Relativity" by N.G. Schultheiss
- "Mirrors" by N.G. Schultheiss
- "Parabolic mirrors" by N.G. Schultheiss
- "Lenses" by N.G. Schultheiss
- "Grinding lenses" by N.G. Schultheiss
- "Telescopes" by N.G. Schultheiss
- "The sky" by N.G. Schultheiss
- "The Universe" by N.G. Schultheiss
- "Colour" by N.G. Schultheiss
- "The Expanding Universe" by N.G. Schultheiss
- "Radio Telescopes" by N.G. Schultheiss
- "An extended Heitler-Matthews model for the full hadronic cascade in cosmic air showers" by J.M.C. Montanus
- "Intermediate models for longitudinal profiles of cosmic showers" by J.M.C. Montanus

About HiSPARC

- "The HiSPARC Detector" by N.G. Schultheiss
- "HiSPARC Detector - Single Detector" by Koos Kortland
- "HiSPARC Detector – Installation" by Koos Kortland
- "HiSPARC Detector - Detector Array" by Koos Kortland
- "HiSPARC Detector - Detector Station" by Koos Kortland
- "de Broglie" by N.G. Schultheiss
- "Fluorescence for high school students" by Niek G Schultheiss and Tom W Kool
- "Primary Particle – Angle" by Koos Kortland
- "Primary Particle – Energy" by Koos Kortland
- "The acceptance of the HiSPARC experiment" by N.G. Schultheiss
- "The field of view of a scintillator pair for cosmic rays" by N.G. Schultheiss
- "Fluorescence for high school students" by N.G. Schultheiss & T.W. Kool
- "The HiSPARC Control System" by R.G.K. Hart et al.
- "Cosmic rays studied with a hybrid high school detector array" by A. Nigl et al.

Project reports from the University of Birmingham

- Locating the Source of Cosmic Rays using HiSPARC Data
- The Effect of the Solar Cycle on Secondary Cosmic Ray Intensity and Cloud Formation
- Evaluating the Accuracy of the Primary Particle Energy Estimations given by jSPARC

Since the project launched in Holland in 2003 (with the UK joining in 2012) there are a huge number of research projects, degree projects, masters projects and PhD theses available to read. These can be found online via the HiSPARC website.
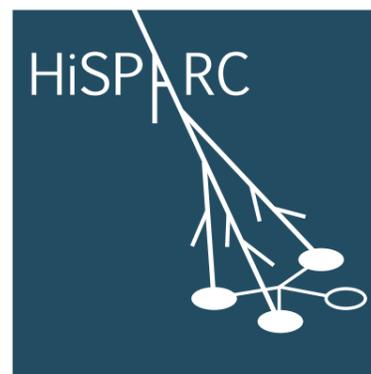
Statistically Significant Variation

- In particle physics statistical significance is often expressed in units of standard deviation or sigma (σ) of a normal distribution.
- The standard deviation is a measure of how widely values are dispersed from the average value (the mean).
- Figure C.1 shows the data collected from a single measurement station. The red bars show the number of coincidences (i.e. number of cosmic rays falling on the detector) per minute. The average is shown by the blue line.
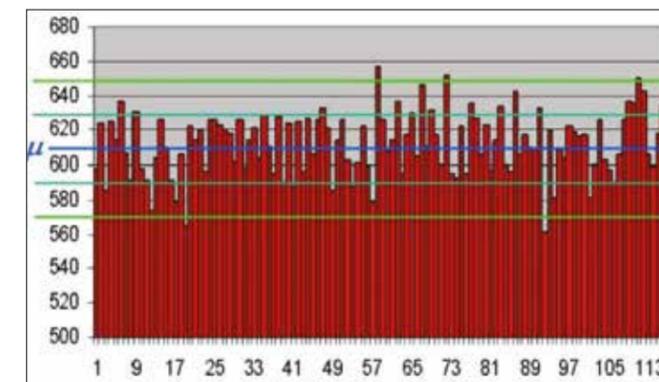

Figure B.1: Number of coincidences against time

It is possible to present the same data using a histogram, where the number of coincidences per minute is plotted against their frequency. Figure C.2 shows the data collected from a single measurement station presented as a histogram. You can see the mean value (615.44) and that 95% of the recorded data lie within ±3 σ from the mean.
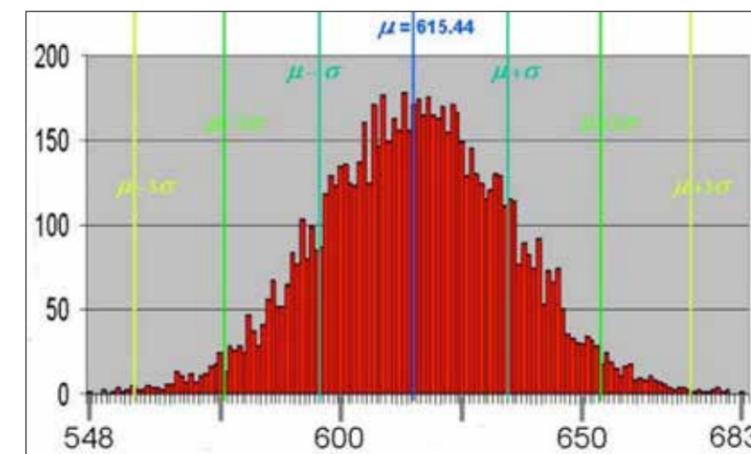

Figure B.2: Histogram of the number of coincidences

- In order to investigate the effects of external factors in cosmic rays, e.g. day-night or winter-summer variation, compare two separate samples of data and decide if they differ enough from each other. Is the variation between these two samples statistically significant? To do this correctly the existing variation within each sample must be taken into account.

- For example: assume that sample 1 has mean μ_1 and standard deviation σ_1 and sample 2 has mean μ_2 and standard deviation σ_2. To decide if the variation between the two samples is statistically significant, carry out the following steps:

1   Calculate the sigma delta (σ_Δ) as:

$$\sigma\Delta = \sqrt{(\sigma_1^2 + \sigma_2^2)}$$

2   Calculate the difference ΔN between the two means:

$$\Delta N = \mu_1 - \mu_2$$

Finally, compare the difference $|\Delta N|$ to the σΔ:
- If $|\Delta N| \geq 5\sigma_\Delta$ then the variation is statistically significant, which means it is possible to say with great confidence that the two samples are different.
- If $|\Delta N| \geq 3\sigma_\Delta$ then the variation is also statistically significant, but the claim that the two samples are different is made with moderate confidence.
- Any relation below $3\sigma_\Delta$ cannot guarantee with confidence that the two samples are statistically significant, due to the already existing variation within the original samples.

Statistically Significant Correlation

- It is possible to investigate the correlation between variables A and B (e.g. A can be the air pressure and B can be the number of events recorded). To do follow the steps below:

1   Choose a timescale (1 day or 1 week etc.) and calculate the averages $\overline{A}$, $\overline{B}$ of both variables within this time frame.
2   Calculate the standard deviations σ_A and σ_B for both variables, for the chosen time frame (use function STDEV.P if using Excel).
3   Calculate the deviation from the average $(A_i - \overline{A})$ and $(B_i - \overline{B})$ for each reading, i.e. difference between the instantaneous measurement and the average for each reading
4   Multiply the two deviations from the average $(A_i - \overline{A})$ and $(B_i - \overline{B})$.
5   Calculate the covariance:

$$\sigma(A,B) = \frac{\sum_{i=0}^{N}(A_i - \overline{A})(B_i - \overline{B})}{N}$$

- If the covariance is a positive number then the two variables are perfectly correlated i.e. if one increases the other also increases.
- If the covariance is a negative number then the two variables are perfectly anti-correlated i.e. if one increases the other decreases.
- If the covariance is zero then the two variables are not correlated.

- Finally calculate the correlation as:

$$\frac{\sigma(A,B)}{\sigma_A \sigma_B}$$

- Perfectly correlated quantities have a correlation of 1; perfectly anti-correlated quantities have a correlation of -1; and independent variables have a correlation of 0.
- The closer the correlation is to 1 (or -1) the greater the statistical significance and thus the confidence that the parameters are correlated (or anti-correlated).

Useful functions on Excel spreadsheets

Function	Explanation
=PI()	Gives the number ϖ (3.14…).
=A2+A3	Adds the values located in the specified cells (e.g. cell A2, A3).
=A2-A3	Subtracts the values located in the specified cells (e.g. cell A2, A3).
=A2*A3	Multiplies the values located in the specified cells (e.g. cell A2, A3).
=A2/A3	Divides the values located in the specified cells (e.g. cell A2, A3).
=A2^2	Calculates the square of the value located in the specified cell (e.g. cell A2).
=SQRT(A2)	Calculates the square root of the value located in the specified cell (e.g. cell A2).
=SUM(A1:A20)	Adds all the numbers that are located in the specified cells (e.g. cells A1, A2…. A20).
=AVERAGE(A1:A20)	Gives the average of all the values that are located in the specified cells (e.g. cells A1, A2…. A20).
=STDEV.P(A1:A20)	Calculates the standard deviation of the values located in the specified cells (e.g. cells A1, A2… A20) using the formula: $$\sqrt{\frac{\Sigma(x - x_o)^2}{n}}$$ where x_o is the sample's average value and n is the sample size (in this example $n = 20$).
=ABS(A1)	Returns the absolute value of the number stored in A1.
=ATAN(A1)	Returns the arctangent, or inverse tangent, of the angle A1. The angle must be in radians and in the range -pi/2 to pi/2.
=ASIN(A1)	Returns the arcsine, or inverse sine, of the angle A1. The angle must be in radians and in the range -pi/2 to pi/2.

Funding

The HiSPARC detector costs around £5k. If you wish to concentrate on analysing and manipulating data there is no need to have a detector. If you are keen to explore the possibilities of installing a detector on the school roof these are possible ideas to start fundraising.

1   Connect with your local University Physics department: they will be able to make some suggestions of grant funders and might be able to collaborate with you to apply for a Royal Society Partnership Grant.

2   The Institute of Physics and the Ogden Trust have regional representatives who can point you to potential sources of funding.

3   Other groups who might appreciate a short talk from your students and who might have small pots of funding are Rotary groups.

4   The school PTA might be willing to support such an innovative research project with potential for publication and conference presentations.

5   Local industry or businesses might be able to help or possibly the Local Enterprise Partnership.

**Image Credit:
NASA / ESA**

Day night variation

Overview

In this analysis activity you will examine data with the aim of establishing if there is a significant variation between the number of events recorded during the day and night.

Data Analysis

1   The first step is to access the article "Data Processing - Periodic Data" by N.G. Schultheiss. This focuses on examining the day-night variation of the muons that reach the detector.
2   Following the instructions in the article download the number of events recorded in a 24 hour period over several days (e.g. first week in September 2013 from Bristol University, 13001)*.
3   Use a spreadsheet and record each day on a separate column (see Figure 1.1).
4   Calculate the number of events during the day, by taking the SUM of events that correspond to 5 hours around mid-day (e.g. from bin 10 to bin 14). Do this for every day of the week.
5   Calculate the number of events during the night, by taking the SUM of events that correspond 5 hours around midnight (e.g. bins 0-2 and 22-23). Do this for every day of the week.
6   Calculate the Average of the day-events (μ_2) and the Average of the night-events (μ_1)
7   Compare the two averages μ_1 and μ_2
8   Plot graphs of the number of day events against time and the number of night events against time to see if there is a clear difference between them.
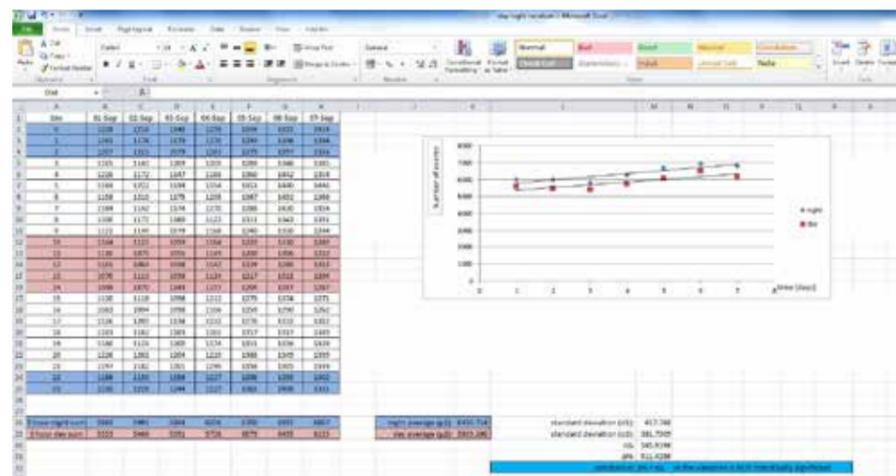

Figure E.1: Day-Night variation, example of spreadsheet calculations (day in pink, night in blue)

Statistical analysis

Use the steps below to check if the variation between day and night is statistically significant.

1   Calculate the standard deviation for the day-events (σ_2) and the standard deviation for the night-events (σ_1) using the function STDEV.P
2   Calculate $\sigma_\Delta = \sqrt{(\sigma_1^2 + \sigma_2^2)}$
3   Calculate the difference ΔN between the day and night averages ($\Delta N = \mu_1 - \mu_2$)
4   Compare the difference ΔN to σ_Δ. If $|\Delta N| > 5\sigma_\Delta$ we can say that the variation between day and night is statistically significant with a lot of confidence. For more details on the significance of the variation see Appendix C, "Statistically significant variation".
5   If you find that the day-night variation is not statistically significant, how can you improve your research in order to make the outcome statistically significant?

Conclusions

- Summarise your findings.
- What have you concluded about the variation between night and day?
- Can you identify other sources that support your findings? Or do they provide a different answer?
- You can submit your work to us at info@researchinschools.org

Further investigations

You can now design your own analysis and could incorporate some of the following ideas:

- increase the statistical significance by considering more days (in similar weather conditions).
- investigate how the outcome is affected by the choice of the time window (5h).
- establish a correlation with the presence of the sun or clouds.
- investigate if this outcome depends on the season.
- Investigate if the outcome depends on the particular station chosen

Effect of pressure on cosmic radiation

Overview

The aim of this analysis task is to identify whether a decrease in pressure is associated with an increase in cosmic radiation (barometric effect).

Data analysis

- This analysis can be completed only if the detector is accompanied by a weather station that records local air pressure and temperature. An example of such a detector is Station: 501 — Nikhef.
- Begin by reading the steps outlined in section 4 of the article "Data Processing - Non-periodic Data" by N.G. Schultheiss.
- Download the number of events recorded per hour for the 1st November 2013 from station 501 Nikhef (it includes a weather station).*
- Download the barometer data for the same day – note that the time is measured in seconds after 1 January 1970, known as UNIX time.
- Subtract the number of seconds from 1/1/70 so that the barometer time starts at zero; then convert seconds to hours.
- Average the pressure readings for every hour so that they can be matched to the events data.
- Create a spreadsheet with three columns: time, events-per-hour and pressure (see Figure 2.1).
- Plot graphs of pressure against time, events per hour against time, pressure against events per hour to see if there is a clear trend, i.e. if they are correlated.
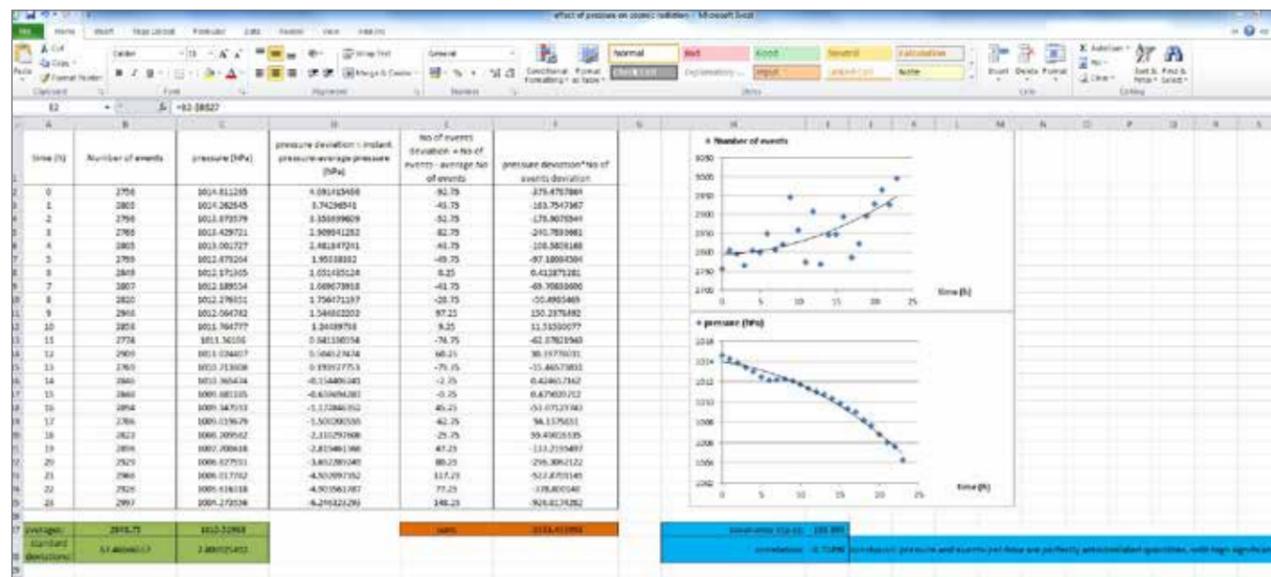

Figure F.1: Effect of Pressure, example of spreadsheet analysis

Statistical analysis

In order to increase confidence in the relation between pressure and number of events follow the steps below:

- Determine the average pressure ($\overline{p}$) and its standard deviation σ_p as well as the average events-per-hour $\overline{e}$ and the standard deviation σ_e for the entire time interval, e.g. 24 hours.
- Calculate the pressure deviation from the average ($p_i - \overline{p}$) for each reading, i.e. difference between the instantaneous pressure p_i and average pressure for each reading. Place these values in a separate column.
- Calculate the events-per-hour deviation from the average ($e_i - \overline{e}$) for each reading, i.e. difference between the events-per-hour e_i and average events-per-hour for each reading. Place these values in a separate column.
- Multiply the pressure deviation from the average with the events-per-hour deviation from the average ($p_i - \overline{p}$)($e_i - \overline{e}$). Place the result in a separate column.
- Calculate the sum of the final column

$$\sum_{i-0}^{N} (p_i - \overline{p})(e_i - \overline{e})$$

and from this, the covariance:

$$\sigma(p,e) = \frac{\sum_{i-0}^{N} (p_i - \overline{p})(e_i - \overline{e})}{N}$$

Where N is the number of data points you have.
- A negative correlation means that pressure and events-per-hour are perfectly anti-correlated parameters i.e. when one increases the other reduces.
- Finally calculate the correlation as

$$\frac{\sigma(p,e)}{\sigma_p \, \sigma_e}$$

A correlation of -1 would mean that the correlation found is statistically significant. For more details on the significance of the correlation see Appendix C "Statistically significant correlation" of the HiSPARC guide.

Conclusions

- Summarise your findings.

- What have you concluded about the effect of pressure on the number of cosmic ray events?

- Can you identify other sources that support your findings? Or do they provide a different answer?

- You can submit your work to us at info@researchinschools.org

Further Investigations

- Try to investigate the same effect from a different station.

- Try to investigate the same effect considering data from a different period in time.

- Investigate the deviation from the general trend on pressure by correlating with other factors (e.g. temperature).

- Try to find out why the number of events in this particular example is so scattered.

- For further details see the article on "Search for a correlation between HiSPARC cosmic-ray data and weather measurements" by Loran de Vries.