Locating the Source of Cosmic Rays using HiSPARC Data

Lewis Anderson

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Contents

Abstract

HiSPARC is an international project designed to allow high school students to take part in real physics research using cosmic ray data measured by detectors set up on the roofs on schools and other academic institutes. The aim of this study was to use data from the HiSPARC experiment to try and identify sources of cosmic rays. In the first method hourly data from 27 detectors over three weeks was analysed to calculate the deviation of the number of events detected compared to a theoretical uniform angular distribution across the sky. This was used to calculate the angle (right ascension) for each detector corresponding to an excess in the number of detected events. Comparing results from all the detectors showed directional peaking in two of the three weeks at different right ascensions but did not correspond to sun location, galactic centre or known super novae. In order to improve localisation a second method was introduced using coincidence data for 6 or more detectors within the Science Park cluster in Amsterdam to triangulate the direction of primary particles for individual showers. Data was analysed for a four day period, where there had been a large number of high energy events detected. This data didn't show a significant deviation from a uniform distribution of primary particle direction across the sky. The first method did find some angular dependence for the direction of cosmic rays but no individual source could be located. The second method did not find any angular variation. Using more detectors in the first method would avoid the need to rebin results in large angle intervals for statistical analysis and would maintain angular resolution. Also the exclusion of right ascensions from detectors with low event deviation (no apparent peaking) should the reduce the spread of results. A possible improvement for the second method could be calculating primary particle energy to see if that had any effect on the direction of the source.

Introduction

Cosmic rays are high energy particles, travelling close to the speed of light, arriving at Earth from outer space. The majority of these particles are protons (85%) with alpha particles (12%) and electrons (2%) the next most common. The nuclei of heavy elements such as Carbon and Oxygen can also be found. When cosmic ray particles, given the name primary particles, enter the Earth's atmosphere they interact with oxygen and nitrogen nuclei to create secondary particles. These particles still have very high energies, although less than the primary particle, and interact further with oxygen and nitrogen nuclei to produce more particles. Repeated interactions create more and more particles resulting in a particle shower which will eventually hit the Earth's surface. *(Kortland, 2014a)*

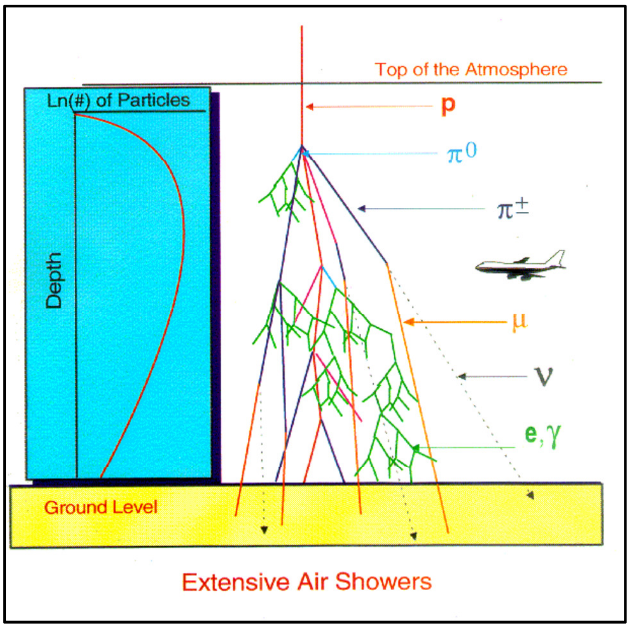

Figure 1. Diagram showing development of cosmic ray shower and constituent particles with particle density as function of depth shown on the left hand side. *(Kortland 2014(a))*

Because Cosmic rays are made up of charged particles they are affected by magnetic fields found throughout the galaxy. They can be accelerated and deflected by them as they travel through the vacuum of space. Higher energy particles are accelerated and deflected less because they are travelling faster. *(Schultheiss 2014)*

Cosmic rays have a large range of energies, from less than 10^9eV all the way to 10^{20}eV with rarity increasing with energy. Particles with relatively low energies (up to 10^9eV) are thought to be produced in our sun and given out as solar winds. *(Kortland 2014(a),(b))* Higher energy particles with energies up to 10^{15}eV are likely to be produced in our galaxy because they do not have enough energy to leave the Milky Way, one likely candidate for their production is shockwaves around super novae. Particles with energies of 10^{19}eV and above are very rare and there are many possibilities for their origins such as active galactic nuclei, neutron stars and super novae remnants. The GZK threshold shows that we should detect very few particles with energies more than 10^{19}eV however the AGASA experiment detected more of these particles than expected, suggesting an unknown source for the acceleration of cosmic rays. *(Kortland 2014 (b), Nagano and Watson 2000, Peters 2014)* It is still unclear what objects in the universe are producing the cosmic rays that we can detect on Earth.

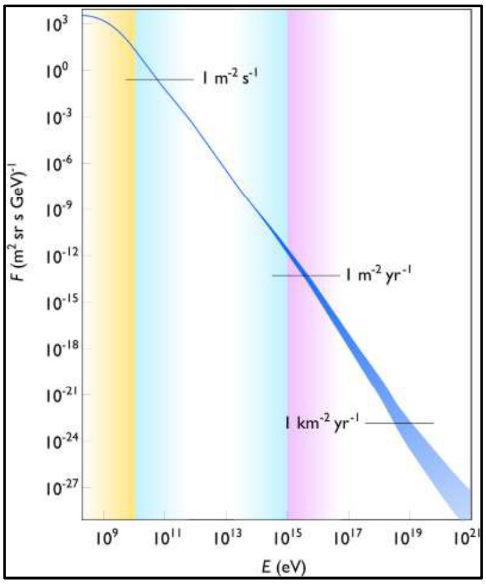

Figure 2. Distribution of energies for cosmic rays hitting Earth. Energy is shown on the x-axis and Flux is on the y-axis. *(Schultheiss 2014)*

HiSPARC (High School Project on Astrophysics Research with Cosmics) is an international experiment designed to study cosmic rays and give high school students the opportunity to take part in and understand Physics research. *(Fokkemma 2012 and Osinga 2014)* Detector stations are made up of two or more detectors are set up on the roofs of participating high schools and academic institutes. Detectors are made up of plastic scintillators that create photons when muons pass through them. These photons travel into a photomultiplier tube which converts the dim flash from a muon hitting the scintillator plate into a measureable electrical current. To remove the effect of instrumental noise so only true showers are detected, an event (shower hitting detector) is only registered when two or more detectors measure a current within a small amount of time of each other – a local coincidence event. Event data collected by individual stations as well as the GPS time of these events and sometimes weather data is sent to the HiSPARC database and made freely available to everyone taking part in the project to use in their own research. *(de Vries 2012)*

Figure 3. HiSPARC detector on roof of Poynting Building at The University of Birmingham.
(Photograph Lewis Anderson)

Methods

Method 1: Calculating angle of event excess

The first method for calculation of direction in sky for the excess for cosmic ray detection was based on techniques described by N.G. Schultheiss *(2012)* and M. Pavlidou *(2014 (b))*.

Data for analysis was collected from the HiSPARC Public Database using a Perl script written by Dr. M. Pavlidou *(2014 (a))*. The dates for analysis were chosen by looking at the event histograms shown on the online database found on the HiSPARC website and looking for a three or four week time period where as many stations had sent information to the HiSPARC Database as possible. The histograms made it clear if any detectors had been turned off or unable to send data in the time period chosen and these detectors could be removed from the analysis. The Perl script also highlighted any times at which no event data were recorded in case any were missed when looking on the HiSPARC website. Data for each detector were downloaded in comma-separated value files (the file extension to which is .csv) which were opened and analysed in Microsoft Excel 2010. Data from three consecutive weeks, beginning 26^{th} May 2014; 2^{nd} June 2014 and 9^{th} June 2014, was used. The number of events detected by the stations for each day was shown in twenty-four separate one hour bins, with bin number 0 being the time between 00:00:00 and 01:00:00. The time recorded for each station is given by the local time zone and measured using an on-board GPS.

For each detector, the event data was organised into individual weeks and a cumulative bin number calculated for each hour of that week. There were 168 bins in each week and each had a value for the number of events in that hour long time period. Each bin was assigned an average time after the start of the time period, so the first bin had a value of 0.5 hours, since the average time after 00:00:00 on the Monday of that week for that hour long bin was half an hour. Using these times the amount the Earth had rotated since the start of the week with respect to the celestial sphere could be calculated. For this the use of sidereal time was needed, since the true time for the earth to rotate with respect to distant stars is not 24 hours but 23 hours 56 minutes and 4 seconds. The equation below was used to calculate how much the earth had rotated for each bin (the angle given by θ in radians):

$$\theta_t = 2\pi \frac{t}{T}$$

Where t is the solar time for each bin in hours and T is the length of a sidereal day in decimal hours (23.93446959 hours).

Instead of the Hann window described by N.G. Schultheiss *(2012)*, the technique was modified to use a Tukey window, with a value for alpha as 0.3, to avoid spectral leakage in the simple Fourier transformation that was to be performed *(Mandel 2014 and Pavlidou 2014 (a))*. The number of events for each bin was assigned a weighting factor, w(n), using these equations:

$$w(n) = \frac{1}{2}\left[1 + Cos\left(\pi\left(\frac{2n}{\alpha(N-1)} - 1\right)\right)\right] \quad When\ 0 \leq n \leq \frac{\alpha(N-1)}{2}$$

$$w(n) = 1 \quad When\ \frac{\alpha(N-1)}{2} \leq n \leq (N-1)\left(1 - \frac{\alpha}{2}\right)$$

$$w(n) = \frac{1}{2}\left[1 + Cos\left(\pi\left(\frac{2n}{\alpha(N-1)} - \frac{2}{\alpha} + 1\right)\right)\right] \quad When\ (N-1)\left(1 - \frac{\alpha}{2}\right) \leq n \leq (N-1)$$

Where b = the bin number, B = the total number of bins and α = 0.3. *(Wikipedia 2014(b))*

Next, as described by Schultheiss *(2014)* and Pavlidou *(2014(b))*, Weighted data was calculated by multiplying the number of events in each bin by their weighting factor. Then the x and y components for all the weighted event data were calculated:

$$Data_x = Weighted\ data \times Cos\ \theta$$

$$Data_y = Weighted\ data \times Sin\ \theta$$

The sum of the x and y components of all the data was calculated and the angle between the direction the detector was facing at the start of the measurement period (00:00:00 on the first day) and the direction where the apparent source could be worked out using the equation:

$$Tan\ \theta = \frac{\sum Data_y}{\sum Data_x}$$

The quadrant in which θ lies was calculated by looking at the signs of $\sum Data_x$and $\sum Data_y$ and was calculated from the following table

Quadrant	$\sum Data_x$	$\sum Data_y$	θ (radian)
1	Positive	Positive	Between 0 and π/2
2	Negative	Positive	Between π/2 and π
3	Negative	Negative	Between π and 3π/4
4	Positive	negative	Between 3π/4 and 2

(Pavlidou 2014(b))

To allow a direct comparison between different weeks the right ascension (α) for the source was calculated from this angle (the right ascension of a star is the same no matter the time or location of an observer). This was done using the equation:

$$\propto = Sidereal\ time\ at\ start\ of\ week +\ \theta$$

The Sidereal time at the start of the week was calculated by using a spreadsheet found online *(Burnett et al. 2014)* and entering the time and date at 00:00:00 on the first day of the week, ensuring it is in Universal Time rather than the time given by the GPS and HiSPARC data as this uses the local time zone. The value taken from the spreadsheet is the value for sidereal time in degrees. At this point θ also need to be measured in degrees.

To ensure the right ascension calculated was given between 0 and 360 degrees, the modulo function (given by MOD(a,b) in Excel and often represented by % in programming) was used in the equation:

$$\propto = MOD(Sidereal\ time\ at\ start\ of\ week +\ \theta + 360{,}360)$$

MOD(a,b) calculates the remainder when a is divided by b. Letting a equal the original right ascension add 360 degrees and letting b equal 360 degrees ensures the outputted right ascension is between 0 and 360 degrees.

Method 2: Triangulating primary particle angle

For my second method the direction of the primary particle was calculated based off methods described in Primary Particle – Angle *(Kortland (c))*.

To start, data was downloaded from the HiSPARC website using the coincidence data download form. Coincidences were downloaded that were detected by six or more stations in the Science Park Cluster in Amsterdam.

For each coincidence, the first three stations to detect the shower were used along with the relative times of the shower detection. The relative positions on the Earth's surface of these detectors had to be calculated in metres by using the latitudes and longitudes. The first station (referred to as Station A from now on) to detect the shower was always given the position (0,0).

First, the bearing of the second of the three stations, station B, compared to station A had to be calculated. This was done in Excel using the formula:

```
Bearing = ATAN2(COS(Lat_a)*SIN(Lat_b)-
SIN(Lat_a)*COS(Lat_b)*COS(Lon_a-Lon_b),SIN(Lon_b-Lon_a)*COS(Lat_b))
```

(Veness 2002)

This uses the ATAN2 function in excel which uses two arguments so the returned angle is given in the correct quadrant.

Next the distance between the stations was calculated using the Haversine formula:

$$Haversine\left(\frac{d}{r}\right) = Haversine(\varphi_1 - \varphi_2) + Cos(\varphi_1)Cos(\varphi_2)Haversine(\lambda_2 - \lambda_1)$$

Where

$$Haversine(\vartheta) = Sin^2\left(\frac{\vartheta}{2}\right) = \frac{1 - Cos(\vartheta)}{2}$$

- d = distance between the two points
- r = radius of the sphere
- φ_1 and φ_2 = latitude of point 1 and latitude of point 2
- λ_1 and λ_2 = longitude of point 1 and longitude of point 2

Rearranged it gives the value of d:

$$d = 2r\,Arcsin\left(\sqrt{Sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + Cos(\varphi_1)Cos(\varphi_2)Sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right)$$

(Veness 2002 and Wikipedia 2014 (a))

In Excel it was written used using the formulae:

```
cellx = SIN((Lat_b - Lat_a)/2)^2+COS(Lat_a)*COS(Lat_b)*SIN((Lon_b-
Lon_a)/2)^2
```

```
celly = 2*ATAN2(SQRT(1-cellx),SQRT(cellx))

distance = celly * 6371
```

(Feed on my Links 2011)

(6371 is the Earth's radius in metres)

Then the relative x,y co-ordinates for B were calculated:

$$x_b = Distance_{a,b} \times Sin\ (Bearing_{a,b})$$

$$y_b = Distance_{a,b} \times Cos\ (Bearing_{a,b})$$

This process was repeated for the third station in the coincidence; station C, giving its relative co-ordinates ($x_{c,}\ y_c$) so that the relative positions on the Earth for all three detectors are known.

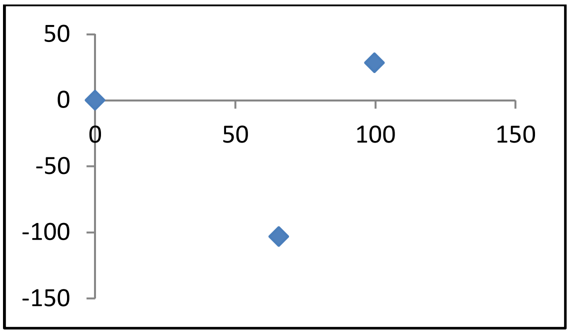

Figure 3. Scatterplot showing relative positions of stations 503, 506, 507. Created using x, y co-ordinates for all three detectors. Distances shown are in metres.

These calculated positions were checked against online calculators and google maps. *(Veness 2002)*

Then as described by Kortland *(2014 (c)),* The relative arrival times for the shower front at each detector was calculated, given once again that station A is the first station to detect the shower front:

$$t_a = 0$$

$$t_b = Time\ of\ detection\ by\ station\ B - Time\ of\ detection\ by\ station\ A$$

$$t_c = Time\ of\ detection\ by\ station\ C - Time\ of\ detection\ by\ station\ A$$

Detection time is given in nanoseconds in the coincidence data so need to be converted into seconds by multiplying the value by 10^{-9}. Using this information, the azimuth and declination of the primary particle can be calculated.

Next the gradient (m) of the line where the shower front intersects the plane of the Earth's surface was found (see fig. 2):

$$m = \frac{y_c \times t_b - y_b \times t_c}{x_c \times t_b - x_b \times t_c}$$

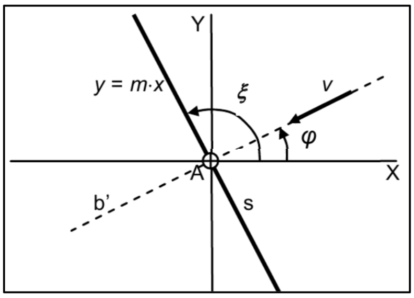

Figure 4. Plan of shower front intersecting plane of Earth's surface (X,Y). Line of intersection is given as y. *(Kortland 2014(c))*

The Azimuth angle (φ) for the direction of the primary particle was calculated by using the equation:

$$\varphi = Arctan(m - 90°)$$

The speed that the shower front travels through the Earth (v) was calculated with the equation:

$$v = \frac{y_c - m \times t_c}{t_c - \sqrt{m^2 + 1}}$$

Note that v > c (speed of light) because the distance the shower front travels though the plane of the Earth's surface is less than the distance it travels through the air. (See fig. 3: distance PQ > distance PQ').

Zenith angle (θ) can now be calculated:

$$\theta = Arcsin\left(\frac{c}{v}\right)$$

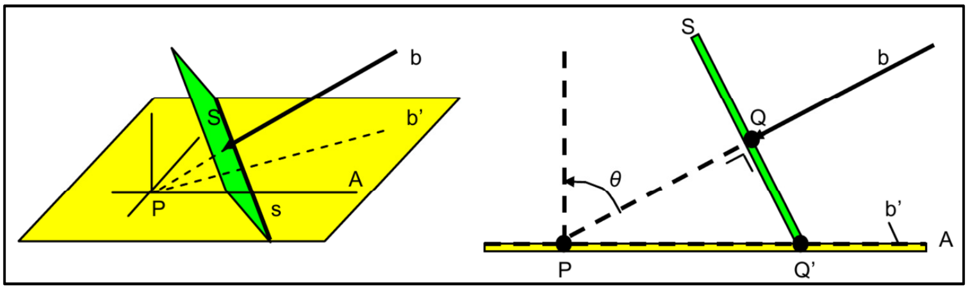

Figure 5. Diagrams showing the shower front (green) meeting the plane of the Earth's surface (yellow). The shower front is perpendicular to the direction of the primary particle (b). Angle θ shows the declination of the primary particle. *(Kortland 2014(c))*

The zenith and azimuth angles for the primary particle direction for every event in the four day period were calculated. Using the event time, zenith and azimuth angles, right ascension and declination for the primary particle direction were found.

To calculate the right ascension, the local sidereal time for each event (LST) needed to be calculated in degrees by using the spreadsheet used in the first method described *(Burnett et al.)*. The average latitude and longitude for all nine stations in the Science Park Cluster was used in this calculation.

The right ascension (α) of the source of the primary particle was calculated from the azimuth angle in excel using the equation:

$$\propto = MOD(LST - \varphi + 360{,}360)$$

(Wikipedia 2014 (c))

Declination (δ) was calculated from zenith angle using the equation:

$$\delta = Latitude - \theta$$

Results

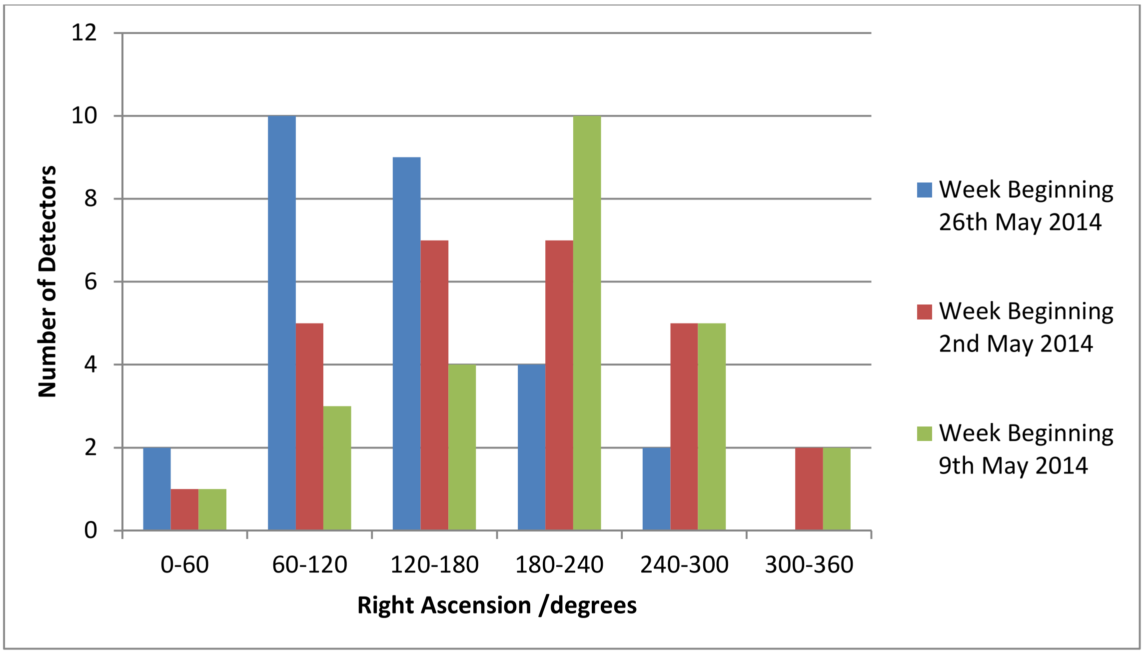

Figure 6. Histogram showing the right ascension of apparent source in the sky from which cosmic rays arrive for three consecutive weeks.

The histogram in Figure 1 shows data from calculations using the first method which allows us to analyse right ascensions for the direction from which most cosmic rays arrive. The data from the 3 weeks are shown on the same pair of axes so any trends for separate weeks can be compared. Overall a wide spread can be seen for all weeks with the largest frequencies lying between 60 and 240 degrees. Possible peaks for each week can be seen in the figure. The peak right ascensions appear to increase with the starting date of each week. The first week shown, beginning 26th May 2014, appears to have a peak somewhere between 60 and 180 degrees. The second week, beginning 2nd June 2013, by comparison has a much broader peak falling between 120 and 240 degrees. The final week, beginning 9th June 2014, has a peak between 180 and 240 degrees.

In order to test whether the right ascension data in each weekly histogram was peaked a Chi-Squared Test was performed against a uniform distribution i.e. assuming that all the detectors would be evenly distributed in the different intervals. For weeks with data from 27 detectors the expected number of detectors in each interval was set to 4.5 and in the week with data from 25 detectors the expected value was 4.17. For the first and third weeks, Chi-Squared shows that the data is statistically different from those of a uniform distribution (weeks starting 26th may $\chi^2 = 18.6$, $p < 0.005$, and 9th June $\chi^2 = 12.2$, $p < 0.05$). Although for the week beginning 2nd June 2014 visually the data is peaked and centred on 180 degrees the distribution is broader than the other two and Chi Squared gives a higher probability that the underlying distribution of angles is uniform ($\chi^2 = 7$, p is approximately 0.2). i.e. there is a 20% chance that peak seen in data are due to random variations in measurement.

A t-test was used to compare the peaks found in data from week beginning 26th May 2014 (mean right ascension = 107, Standard deviation = 79, n = 27) and week beginning 9th June 2014 (mean right ascension = 160, Standard deviation = 98, n = 25).The distributions from the first and third weeks were found to be significantly different at the 5% level. ($t = 2.2$, $p < 0.05$). Data from the second week was not used in the t-test comparison because the chi-squared test showed there was a 20% probability the data was not peaked.

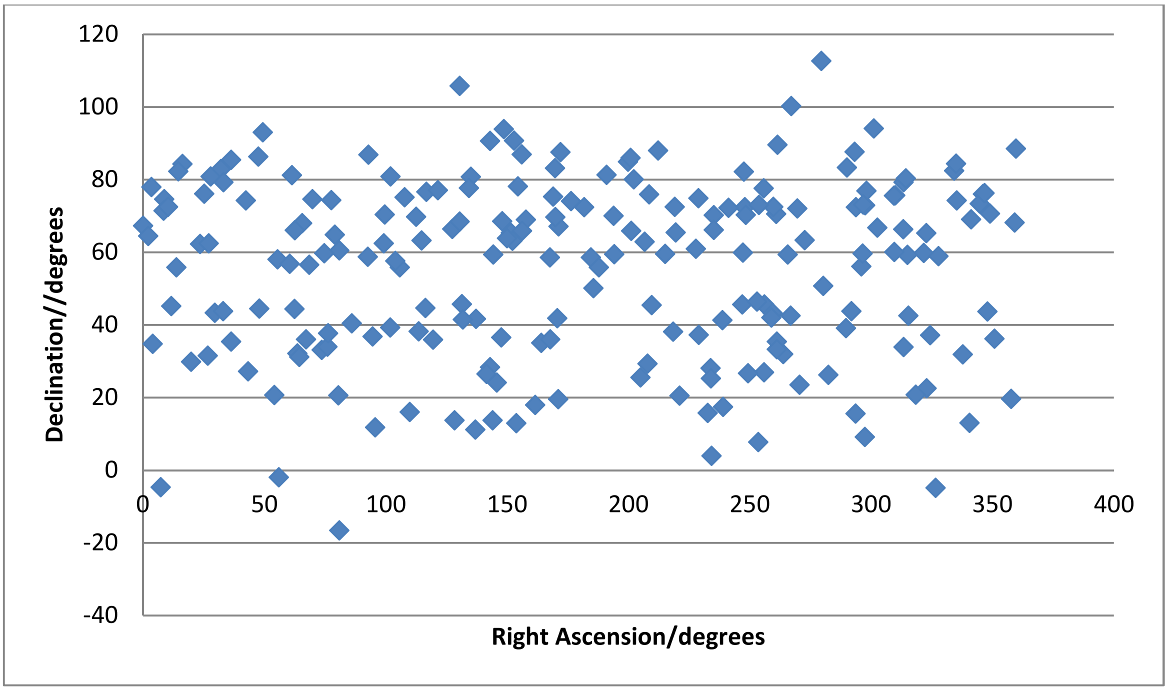

Figure 7. Right ascension and declination of arrival of primary particle for showers detected over four consecutive days in February 2014.

Figure 2 is a scatter plot showing the arrival directions of primary particles calculated with the second method. All points appear to be random with little visible clustering or correlation. The right ascensions of arrival directions cover the whole range of 0 to 360 degrees and almost all declinations lie between 0 and 90 degrees.

Due to experimental effects resulting in declinations directly over-head being detected more easily, only Right Ascension data was used further in statistical analysis.

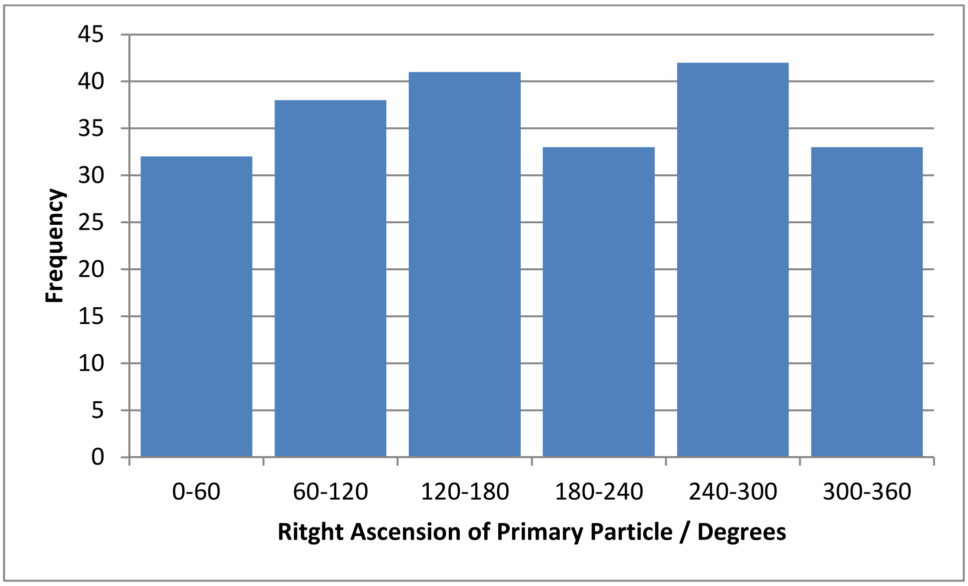

Figure 8. Histogram showing the right ascension for the direction the primary particle arrives in for events detected over four consecutive days in February 2014.

Figure 3 is the result of this analysis. It shows a histogram with right ascension of primary particles plotted against their frequency. This more clearly shows a uniform distribution of angles. A Chi-Squared test was used again comparing the data in the histogram of that which you would find of a uniform distribution of angles all the way from 0 to 360 degrees, this meant that the expected value were set to 36.7 for all intervals. χ^2 was calculated to be 2.6 giving p a value of 0.75. This meant that there is a 75% chance that right ascensions of primary particles are in fact uniformly distributed.

Discussion

Previous work has been able to suggest sources of ultra-high energy cosmic rays due to shock acceleration in super novae remnants *(Koyama et al. 1995)* and also source of excess cosmic ray flux coming from areas near to the galactic centre and active supernovae *(Bellido et al.)*. This project was conducted try to find out if the HiSPARC database would be able to locate some of these sources, so the data chosen to analyse was taken from dates where there were known super novae (information was gathered from an online database *(IAU Central Bureau for Astronomical Telegrams 2014)*) had occurred and would be "visible" from the northern hemisphere. The peaks in frequency of calculated right ascension for areas of the sky contributing excessively to the shower detection found in the first analysis could point to sources of cosmic rays.

Before starting to analyse data it was first checked by looking at histograms on the HiSPARC database. A large variation in shapes could be seen in these histograms. Some were almost entirely flat, some showed peaks at different times and some showed clear 24 hour fluctuations. All of this data was analysed to see if there was a common source for all or some of the detectors.

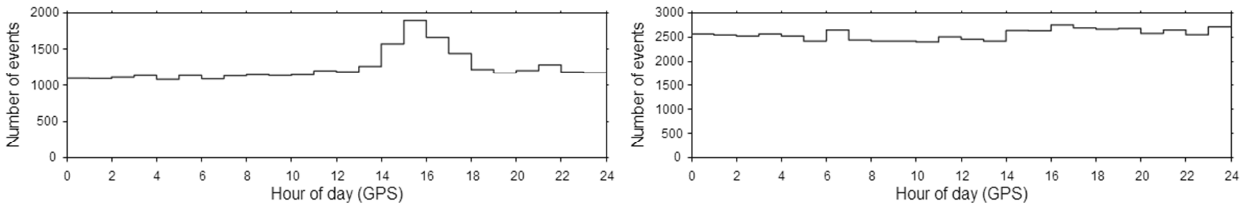

Figure 9. Histograms representing event data from 26th May 2014 for two stations. Station number 5 (left) and station number 501 (right). This an example of the different shapes seen in the raw data, data from station 5 shows a large peak at around 16 hours compared to data from station 501 which is pretty much uniform. Taken from the HiSPARC Database.

Using the histograms peaks in the number of stations detecting an excess of cosmic rays from a certain directions were found. The right ascensions of these directions against the celestial coordinates of the super novae from the database as well as the location of the galactic centre and the sun at the time of the measurements, were checked against these results, but no correlation was found. The right ascension data was checked against the locations of supernovae remnants that were "visible" in the northern hemisphere, as these could be the source of cosmic rays that cause the showers detected by the HiSPARC detectors. The closest remnant found with a declination that meant it could be seen from the detectors was SN1054, 6,300 light years from Earth, and could be found at a right ascension of approximately 85 degrees, somewhere in the middle of the peak found in data from the week beginning 26th May 2014. However if this was actually a source of a large amount of cosmic rays causing the large peak found in the data, the same effect in all three weeks would be expected because the remnant would produce cosmic rays for a large time period, but each week had peaks at different right ascensions.

A Tukey window with a value 0.3 for α was used to weight the event data. A Hann window was originally used in the method described by Schultheiss *(2012)* but the Hann window caused any peaks in the event data downloaded falling near the end of beginning of the week to be smoothed. So a Tukey window as suggested by Dr Ilya Mandel was used. Eventually a value for α as 0.3 was chosen. Testing for different values of α was done, starting with α = 0.05 as suggested by Dr Mandel. The value of 0.05 for alpha meant that 8 hours of the week were weighted a lot compared to all the other hours which were given weighting factors of. These weighted times corresponded to a specific angle in the sky which meant that for model data that was entirely uniform where no direction should be found, false angles were still being calculated with high percentage deviances because the weighting factor was creating troughs in the data. Many other values for alpha were tested but a value of 0.3 was chosen, as this calculated the correct right ascension for the model data most accurately. To conduct the test, data with peaks at the same angle in the sky each day was created so how much the weighting affected the final result could be checked, a value of 0.3 gave an angle closest to the one created in the model data and what was expected. The value for 0.3 weighted only all of the first and last day of the data, leaving 5 days un-weighted which was better than the Hann window, and by weighting the whole of a day meant that all angles were weighted equally because in the 24 hour period, the Earth rotates a full 360 degrees.

Unfortunately the accuracy of this analysis was not very high. The event data from the HiSPARC database was binned into hour-long periods so the maximum resolution of any calculations is already 15 degrees (the amount of rotation by the earth in one hour) and lack of collimation in the individual detectors means they can detect showers coming angles greater than this, this lead to results with a very low angular resolution. Data from only 27 detectors was available because of the amount of downtime on many stations in the HiSPARC network; this meant that data had to be re-binned into 60 degree intervals to allow me to use the Chi Square test to analyse because otherwise there would be very low expected frequencies for all intervals with data that was already very noisy. 60 degree intervals meant a lot of angular resolution was lost and results smoothed but was necessary to use Chi Square as recommended. Weather variation and day-night variations in cosmic ray shower detection could also have a huge effect on the results. If these had occurred at certain times of each day that either causes more or less than usual the amount of events to be detected, these would be attributed to different angles in the sky rather than conditions here on Earth, a possible explanation for the peaks seen in the calculated right ascensions. As the number of detectors in the HiSPARC network increases this method may become more effective because the histograms and chi-square test could be binned in smaller intervals, however another method which reduces the effect of conditions on earth would be better. The method also calculated the percentage deviation for each angle calculated. An improvement in the method would be to use this percentage deviation to weight the right ascensions calculated from individual detectors when calculating a mean right ascension. Every detector generates a right ascension but this weighting would mean that those detectors where there was really no significant excess would have less effect on the final mean.

The second method was used because to solve many of the problems found in the first method. By using individual coincidences a much greater number of data points was generated, 220 points compared to just 27 in the first method. Each piece of data was also much more precise they were for individual coincidences rather than data binned into 15 degree intervals (angle covered by rotation of Earth in one hour). This method also had the advantage that a declination could be calculated as well, being able to identify sources as points on the celestial sphere with both ordinates rather than just one.

Coincidences from six different stations were used to try and limit the energy of the showers that were analysed. Higher energy primary particles were expected to produce wider shower fronts which would be detected by more stations, so coincidences between six or more detectors were used to reduce the number of low energy showers analysed *(Lazzeroni 2014)*. But the number of stations needed for a coincidence wasn't made too large so got a larger data set was collected. The four dates analysed were chosen because Arne de Laat from HiSPARC Nikhef suggested February 2014 as a month where there were quite a few high energy events.

The second set of results were quite different from the ones produced by the first method. After no visible clustering in the directions in the scatter plot were seen, only right ascension data was used for statistical testing because Declinations that were directly overhead the detectors could be more likely to register coincidences more than those just inside the cluster's field of view due to the way stations detect events (they present larger surface area to events directly overhead), buildings around the stations that could block showers coming more horizontally and more absorption of secondary particles at oblique angles having to travel through greater thickness of atmosphere. The right ascension results showed a much more uniform distribution of cosmic ray sources and the Chi Squared test proved this. This suggests that no area in the sky appeared to be producing more cosmic rays than anywhere else during this monitoring period and individual sources could not be located using this method.

There were a number of assumptions made that means results were not entirely accurate, The shower front was assumed to be flat and moving at the speed of light and the Earth was assumed to be flat with all stations at the same height leading to errors in the angles calculated. However, the effect on the final results caused by this would not be enough to stop clustering or peaking in results.

It is also possible that the direction of the primary particle that was calculated may not be in the direction of its source since the path of cosmic rays are bent by magnetic fields of stars, the Earth and other celestial bodies. If only very high energy cosmic rays were used this effect would be minimised, since they travel faster so their paths are bent less by magnetic fields. Higher energy cosmic rays may also be more likely to come from a common source as shown by Bellido and others *(2001)*. If the method used for triangulating was used in conjunction with energy reconstruction of the primary particle as described by Kortland *(2014(d))* and like what is currently done using jSPARC and being developed further by those working at HiSPARC in the Netherlands, Primary particle direction could be calculated along with its energy to find if cosmic rays with certain energies can be attributed to specific sources.

Since the second method used did not find any sources of a high flux of cosmic rays but the first method did show some parts of the sky produced an excess at some times, it would be interesting to see what would happen if the second method was used for the time period for the same time period was the first to see if that found similar results or any clustering. If it did this could be attributed to short lived sources of cosmic rays and the processes should be repeated for a much longer period of time to see if a similar results occurred throughout the year. The calculations involved in the two methods could have been done more efficiently if a program for them was written since working with Excel took a large amount of time to process a relatively small amount of event and coincidence data, HiSPARC also offers a lot of support for things like this with their open source Python and Javascript code.

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Lazzeroni C. (2014) University of Birmingham **Personal Communication**

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