HASP Student Payload Application for 2012

Payload Title:

Directional Cherenkov Detector

Payload Class: (check one)	Institution:	Submit Date:
▯ Small ▯ Large	Louisiana State University	December 16, 2012

Project Abstract

The purpose of this project is to create a prototype cosmic ray charge detector for the use in the Calorimetric Electron Telescope (CALET) project. The proposed detector system design utilizes Cherenkov radiation emissions to measure the charge, up to 6 charge units, of primary cosmic ray particles. Essentially, the primary goal for the directional Cherenkov detector project is to effectively identify incoming cosmic ray particles as hydrogen, helium, lithium, beryllium, boron, carbon, or heavier cosmic ray nuclei.

Team Name:	Team or Project Website:
Team Electron Volt (TeV)	

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Mission Goal

Investigate the primary cosmic ray spectrum in the stratosphere by prototyping a directional Cerenkov detector for use by the Calorimetric Electron Telescope (CALET) project.

Objectives

1. Develop a directional Cerenkov detector for flight on HASP (High Altitude Student Platform)
2. Resolve the charge (Z) of primary cosmic ray events for ions of $Z \leq 6$, for the purposes of identifying the cosmic ray ions
3. Determine a flux measurement for each of the identified cosmic ray ions
4. Construct a detector system which is verified to function in simulated flight conditions
5. Integrate with flight vehicle

Requirements

Functional Requirements

- Payload shall exceed an altitude where secondary particles are at a negligible flux (above 80,000 feet)
- Payload should not measure back-scatter particles
- Payload shall record altitude data within 5000 feet to ensure that the device detects primary cosmic rays with negligible secondary cosmic ray events
- Data acquisition system should continue to acquire interpretable data after power restart

Performance Requirements

- Primary cosmic rays with a charge $Z \leq 6$ shall be separated by charge
- Detector shall have a high enough charge resolution (0.3 e) to distinguish particles having a charge of $Z \leq 6$
- Detector shall record at least 100 counts of each primary particle ($Z \leq 6$) in order to ensure statistical reliability of data

Environmental Requirements

- The payload shall be able to operate within temperatures of -70 C and 35 C
- The payload shall be able to operate within pressures of 5 and 1000 millibars

Deployment Requirements

- Payload power system will be activated remotely, before launch

Operability Requirements

- The entire payload system shall be assembled and tested as a system before flight
- PMTs should be coated and verified not to arc before flight
- Payload shall be thermally tested in simulated flight conditions before flight
- Payload shall be pressure tested in simulated flight conditions before flight

Management Requirements

- A risk assessment and mitigation plan shall be established
- A Gantt chart should be made and adhered to

Design Requirements

- The payload shall be powered with voltages of 29V to 33V and under 2.5 amps
- The payload shall remain secured to the HASP mounting plate under a 10 g vertical and 5 g horizontal shock
- Payload shall weigh less than 20 kg
- The payload shall have a footprint under 38 cm by 30 cm and a height under 30 cm
- Payload shall have a serial downlink of data under 4800 baud

Science Background and Justification

Cosmic Rays

Cosmic rays are highly energetic charged particles, which are generated by certain stellar phenomena. Aside from the particles generated from solar flares, cosmic rays originate outside the solar system. Since the trajectory of the cosmic ray is affected by various complex stellar magnetic fields, the exact origin of each cosmic ray cannot be determined. However, the composition and energy spectrum of cosmic rays can be observed, and these properties point toward possible galactic sources of cosmic rays. A variety of detector systems are designed and utilized to test the validity of these theories of origin. Some detectors, like those found at the Pierre Auger Observatory, exist as part of an array of devices on the earth's surface. An alternative, to placing detectors at ground level, is measuring cosmic rays at high altitudes. High-altitude balloons are ideal vehicles for carrying and supporting detector systems in upper-atmosphere environments. In addition to high-altitude balloons, many detector systems, such as the CALorimetric Electron Telescope (CALET), utilize space vehicles to run experiments above the earth's atmosphere.

CALET project

The purpose of our mission is to develop a prototype device for use in the CALorimetric Electron Telescope experiment. Set to launch in 2013, CALET is designed by Waseda University to search for the sources of primary cosmic rays, details of their transportation, and signatures of dark matter. Their research involves making detailed measurements of the electrons entering the atmosphere. Collecting data on these high-energy electrons will provide the CALET mission with the information they need to learn more about high-energy astrophysical phenomenon. CALET intends to investigate the natural acceleration processes experienced by cosmic ray electrons. Theoretically, the highest energy electrons should have relatively identical origins compared to the other electrons, making it possible to identify specific sources such as supernova explosions, black hole accretions, and Active Galactic Nuclei (AGN) jets. By the end of their mission, CALET will obtain information on high-energy electron production and transportation. The energy range being detected will be from 1 GeV to 20 TeV. Similar in concept to our own project, the CALET mission will also be to distinguish charges and measure cosmic ray nuclei fluxes up to 1,000TeV. CALET's high-energy capability is what makes it possible to detect signatures of dark matter particle interactions. Some of these dark matter candidates, such as Kaluza-Klein particles, have relatively high kinetic energies up into the TeV range.

Interaction With the Earth's Atmosphere

A cosmic ray particle is typically classified as either a primary or secondary particle. Primary particles are comprised of naturally occurring atomic nuclei and beta particles. A primary particle originates at a source and travels through the vacuum of space until it interacts with matter. The interaction between the primary particle and matter, such as the air molecules in the earth's atmosphere, results in the fragmentation of the primary particle into one or more secondary particles. Depending on the total relativistic energy of the originating primary particle, the secondary particle(s) produced can be composed of differing amounts of kaons, pions, mesons, muons, and a myriad of other subatomic particles with charges of either 1 or -1 elementary charge units. These secondary particles can proceed to either decay or interact with other air molecules, producing more secondary particles. In some cases, one highly energetic primary particle can result in a cascade of numerous secondary particles. Since the probability that a cosmic ray will interact with air molecules increases as the atmospheric density increases, the intensity of primary cosmic rays tends to decrease rapidly as altitude decreases from 80,000 feet to the earth's surface. Therefore, an essential requirement, to observing exclusively primary cosmic rays, is to exceed 80,000 feet. This is where a sufficient primary cosmic ray flux exists and the secondary cosmic ray flux is kept to a minimum.

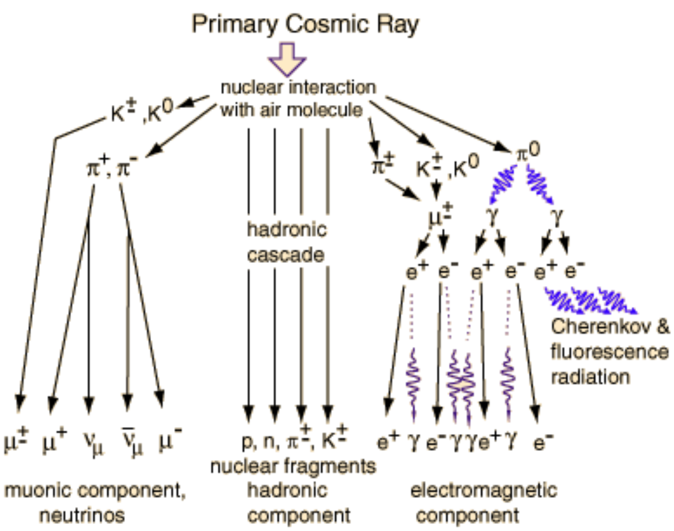

Figure 1: Interaction with the Earth's Atmosphere (Nave)

Cosmic Ray Flux

Table 1– Primary Cosmic Ray Fluxes

Cosmic Ray Nuclei	Total Flux (counts/m^2 s sr)
Hydrogen	354.7
Helium	103.1
Lithium	0.97
Beryllium	0.28
Boron	0.68
Carbon	2.36

Data on primary cosmic rays is provided by previous research experiments and models in the form of a plot of differential fluxes verses kinetic energy per nucleon. The data must be integrated over kinetic energies ranging from the geomagnetic cutoff to infinity in order to obtain a total flux for each cosmic ray nuclei, shown in Table 2.

The Cherenkov Effect

Cherenkov radiation occurs when a charged particle, such as a cosmic ray, transverses through an insulator at a velocity exceeding the speed of light in the material. The Cherenkov light has specific properties that are related to the speed and charge of the incoming particle (Fernow). The intensity of Cherenkov radiation can be measured using photomultiplier tubes (PMTs). The equation for the intensity of the Cherenkov radiation, shown in Equation 2, is a function of two variables, the relativistic speed of the incoming particle (β) and the charge of incoming particle (z).

$$\int_0^N \mathrm{dN} = \int_{x_1}^{x_2} 2\pi\alpha z^2 \left(1 - \frac{1}{n^2\beta^2}\right)\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\mathrm{d}x \qquad [2]$$

Since there are two unknown variables, two radiators, Lucite and lead glass with different indexes of refraction, n_{lucite}=1.49 and $n_{lead\ glass}$=1.70, are needed in order to deduce the charge of the cosmic ray particle.

Overall System Design

The system is designed within the constraints of a large payload configuration.

Power System

The individual subsystems have vastly different power requirements. The power board converts the 30V input from HASP into the appropriate voltages for each individual subsystem. The 30V input from HASP is first attenuated to 12V by an onboard DC-DC converter. The EMCO C15 high voltage converters, control board, and pulse height analyzers require this 12V input. Three high voltage converters are required in order to mitigate the effects of high voltage arcing across the electronic components. Each of these high voltage converters has a controllable output voltage, which is necessary in calibrations and mitigating the occurrence of electrical arcing. Four current sensors monitor the current draw of the individual subsystems. Three 250 mA fuses ensure that the current draw from any electrical arcing does not draw more than 2.5 mA. Finally, four relays are included so that each subsystem can be switched on and off by the control system.

Detector System

The detector system consists of two radiators. The top radiator consists of UVT-Lucite, and the other radiator consists of lead glass. Each radiator has its top surface painted with black UV absorbent paint. In addition to blocking ambient light, this paint also filters Cherenkov signals from upward trajectory particles. On each radiator, five wavelength-shifting bars shift the UV Cherenkov radiation into the visible blue spectrum. The PMTs have a peak spectral response in the visible region. WLS bars are needed to shift the UV Cherenkov light into the visible region for the PMTs to measure. Additionally, the WLS bars internally reflect the Cherenkov radiation into the light guides attached to each of the PMTs. Five R5611 PMTs are used per radiator and are attached to light guides connected to each WLS bar. The bases of the PMTs are coated with DP-270 epoxy to prevent electrical arcing and coronal discharges in low-pressure environments.

Signal Processing System

The signal processing system contains two important subsystems, the pulse-height analyzer and the logic boards. The pulse-height analyzer filters electronic noise by utilizing discriminators, samples the PMT output current pulse, produces an analog signal proportional to the pulse-height, and holds that analog signal long enough for the analog to digital converter (ADC) to read that signal. These functions are essential in order to convert the quick PMT current pulse into digital value that can be analyzed in the determination of the charge of the incoming cosmic ray particle. The logic gates are needed to assess if the PMT pulses are in coincidence with each other. An event requires that both radiators produce signals. Single events are counted, but the pulse height of the signal is not measured.

Control System

The control system consists an Arduino microcontroller with ten additional temperature sensors and two rate counters. Each PMT signal output must be routed into the ADC on the microcontroller board. The ADC is needed to convert the analog signals from the pulse-height analyzer and convert each of them into a digital value that can be processed into a digital format. Ten Temperature sensors, positioned throughout the payload, are used to monitor the temperature of all of the payload subsystems. Rate counters are used to monitor the number of events from each radiator. A dramatic increase in the singles rate indicates possible arcing in one or more PMTs. The data from the PMTs, sensors, and counters will be sent via serial telemetry to ground in a data format specified in the telemetry rate section. Additionally, the processor shall receive uplink commands. These commands are processed and executed by the microcontroller.

Payload Specifications

Power Specifications

The power on HASP for large payloads is limited to 2.5 A at 30 V, which is 75W. The power budget for the payload is located in Table 3.

Table 2 – Power Specifications

Subsystem	Voltage (V)	Current (mA)	Power (mW)
PMT (1-5)	1250	1	1250
Detector Readout	12	300	3600
Control	7	142	1055

The photomultiplier tube system uses 1.25 W. This conclusion is based on a measurement of a current draw from ten R5611 PMTs with of 1mA at 1250V. The pulse height analyzer system includes 3 boards drawing a total of 300 mA of current at 12V. The power for a four-channel pulse height analyzer board coupled with a DC/DC converter is measured to be 3.6 W. The control system draws 142 mA at 7V. The power usage for the control subsystem is measured to be 1.055 watts. The subsystems use a total of 5.905W. Considering a minimum 50% power conversion efficiency of the DC/DC converter, the system should use no more than 8.9W. This is well below the 75W provided by HASP.

Weight Specifications

Table 3 - Payload weight decomposition

Component	Measurement Method	Weight (g)
PMTs with coated bases	Estimated	550 ± 10
Pulse Height Analyzer System	Measured	618.6 ± 0.1
Control System	Estimated	116.4± 0.1
Power system and wiring	Measured	239.1 ± 0.1
Lucite radiator w/WLS bars	Measured	354.9 ± 1
Lead glass radiator w/ WLS bars	Measured	872.3 ± 1
Mechanical structure	Estimated	5000 ± 100
Total		7900 ± 100

The maximum weight for large HASP payloads is 20kg. The weight budget for the payload is located in Table 4. The mass of a R5611-01 PMT and a PMT circuit base used for a previously flown cosmic radiation payload was measured to be 45 grams. Since there will be 10 PMTs and bases, the total amount of mass of the PMT system is measured to be about 450g. The epoxy coat on the PMTs and the bases, used to prevent arcing, is estimated to weigh about 100g. Three boards comprising the signal analysis subsystem are required. The total mass of these three boards is 618.6g. The control system subsystem including the counters, sensors, and Arduino microcontroller is measured to be 116.4g. A weight of 239.1g is measured for the power board and power connectors. The weight of the Lucite radiator with the WLS bars is measured to be 354g. The lead glass with WLS bars is measured to weigh 872.3g. The mechanical structure is estimated using the volume needed by the payload. Aluminum supports are needed to withstand the vertical shock. Foam insulation is needed insulate the payload from cold temperatures. The individual radiators must be supported and kept 17 cm apart. The strain on the optical bonds must be kept to a minimum. The entire structure is estimated to require 5000g of material. 7900 grams is the estimated total weight. This is less than 20000-gram limit provided by HASP for large payloads.

Telemetry Specifications

Table 4 - Data Record Format

Bytes	Bits	Description
1	0-7	Type
2-5	0-31	Timestamp (UNIX time)
6	0-7	Least significant 8 bits of checksum
7-26	0-159	Pulse height PMTs 1-10

The format for the data record for the payload is in Table 5. The first byte is used to read out the type of record. There are two types of records that the payload will send: a data record and a status record. Each type of record will have a unique first byte. The second through fifth bytes of the data record include a timestamp in UNIX time. The sixth byte is the least significant 8 bits of the current data record so the data record can be checked for transmission errors. Bytes 7 through 26 are used for the pulse heights of each photomultiplier tube for each coincidence. 2 bytes have been allocated for each PMT pulse height. The total byte usage for each data record is 26 corresponding to a total number of bits of 208. The data record will downlink every time there is a coincidence event, which is approximately 96 times a minute.

Table 5- PMT Status Format Record

Bytes	Bits	Description
1	0-7	Type
2-5	0-31	Timestamp (UNIX time)
6	0-7	Least significant 8 bits of checksum
7-16	0-79	Temperature sensors
17-19	0-23	Singles count (PMTs 1-5)
20-22	0-23	Singles count (PMTs 6-10)
23-25	0-23	Current sensors
26	0-7	Last command entered

The format for each status record is shown in Table 6. The first byte signifies that the record is of a status type. Bytes two through six are the same as in the data record. Bytes seven through eight show the status of each PMT. Ten temperature sensors require 10 bytes of data. Three bytes will allow for 16,777,215 counts, which is much more than would be expected within a period between since the last status record. Therefore, six bytes are needed to send the singles count for each radiator. There are three current sensors, which require 1 byte of serial data each. Finally, the last uplink command issued is sent as 1 byte. The total number of bytes calculated for each status record is 26, which corresponds to a total of 208 bits. The status record is set to downlink every 100 seconds.

The expected coincidence rate of the detector at HASP float altitude is 96 events per minute. Allowing for a 20% uncertainty in the expected coincidence rate of the detector, the bit rate of the data record is estimated to be 23,920 bits/min. The bit rate of the status record is estimated to be 125bits/min. The total data rate is 24,045 bits/min or 401 bits/s. This bit rate is within the limits of the HASP large payload telemetry rate constraint, which is not to exceed 4800 baud.

The payload will also utilize an uplinked data. GPS timestamps are needed in order ensure the data record timestamps are accurate. A command to turn on the relays is required to systematically “boot” the payload system. This ensures that the current draw will not spike as each subsystem is turned on individually. Commands to turn off relays may be necessary in the event of electrical arcing or overheating. The high voltage converters have an adjustable voltage output. They can be controlled via an analog signal sent from the digital to analog converter on the Arduino microcontroller. A command to reduce or increase the voltage output of the individual high voltage converters may be necessary in the event of arcing.

Team Management Structure

Team Electron Volt is comprised of Sean McNeil with faculty advisor Dr. Gregory T. Guzik. Contact information and individual roles are shown in Table 7.

Table 2 – Team Management Structure

Name	Sean McNeil	Dr. Gregory T. Guzik
Roles	• Software • Testing • Calibrations • Data Analysis • Project Management • Electrical • Mechanical	• Faculty Advisor
Department	LSU Physics and Astronomy	LSU Physics and Astronomy
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