ICARUS I & II: INVESTIGATING COSMIC SHOWERS THROUGH UNDERGRADUATE RESEARCH INVOLVEMENT

by

E. G. Jellison

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Thesis Supervisor:

Blagoy Rangelov

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DEDICATION

To the Texas State University Department of Physics for giving me a chance.

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ABSTRACT

Cosmic showers are a phenomenon where high-energy particles from space interact with matter in Earth's atmosphere, decaying into secondary particles in a showering pattern. One of these secondary particles, the muon, has the innate ability to travel longer through the atmosphere before decaying further than any other secondary product of cosmic showers. Because of this ability, the muon flux gradient as a function of altitude can be measured to study atmospheric conditions and to better understand the muon. Icarus I & II were high-altitude balloon missions launched to measure the muon flux gradient over central Texas. The design for Icarus was intended to be used again for future high-altitude balloon missions and to encourage further undergraduate research involvement. Both Icarus missions were launched and retrieved successfully while Icarus II recorded atmospheric data and the muon flux gradient. Here we present the preliminary results of our findings.

I. INTRODUCTION

Muons are subatomic particles with the same charge and spin as electrons but more mass (Povh, et al. 2008, Particle Data Group 2021). Their abundance comes from the decaying of products produced by collisions of cosmic rays and particles in our atmosphere (Siingh and Singh 2010). As these muons travel further into our atmosphere, they too decay into other particles. However, what makes muons unique is their ability to survive further distances than most other subatomic particles while interacting with matter. Their presence has been recorded on the surface of Earth and even further below (Bernero, Olitsky and Schumacher 2013, Cecchini and Spurio 2012). Muons are the most numerous charged particles showering down on the Earth's surface. Still, questions remain about how effective and to what degree Earth's atmosphere acts to decay them as they pass through. The Icarus missions were high-altitude balloon missions designed to address these questions and to help develop a student body at Texas State University in San Marcos focused on further space exploration research.

Cosmic rays are high-energy particles (primarily protons or helium nuclei) or gamma-rays created from various high-energy events in space (Dorman 1981). When cosmic rays of enough energy enter Earth's atmosphere, their interaction with matter in the air may cause the cosmic ray to decay into a cascade of secondary particles. This cascade of particles diffusing away from each other is a phenomenon known as a cosmic shower (or air shower) and was first discovered in 1934 (Rossi and Greisen 1941).

The primary first product of a particle cosmic ray interaction in Earth's atmosphere is a subatomic particle called a pion $(\pi, \pi^{\pm})$. These particles are unstable and will quickly decay further into more secondary particles. Figure 1 shows the possible decaying process based on the pion that was first created. If the pion is neutral (π), it will decay into two photons (γ) in the process: $\pi \rightarrow \gamma + \gamma$ creating an electromagnetic cascade. If the pion is charged $(\pi^{\pm})$, they will decay into muons and neutrinos in the following processes: $\pi^- \rightarrow \mu^- + \upsilon$ and $\pi^+ \rightarrow \mu^+ + \upsilon$ (Rao and Sreekantan 1998).

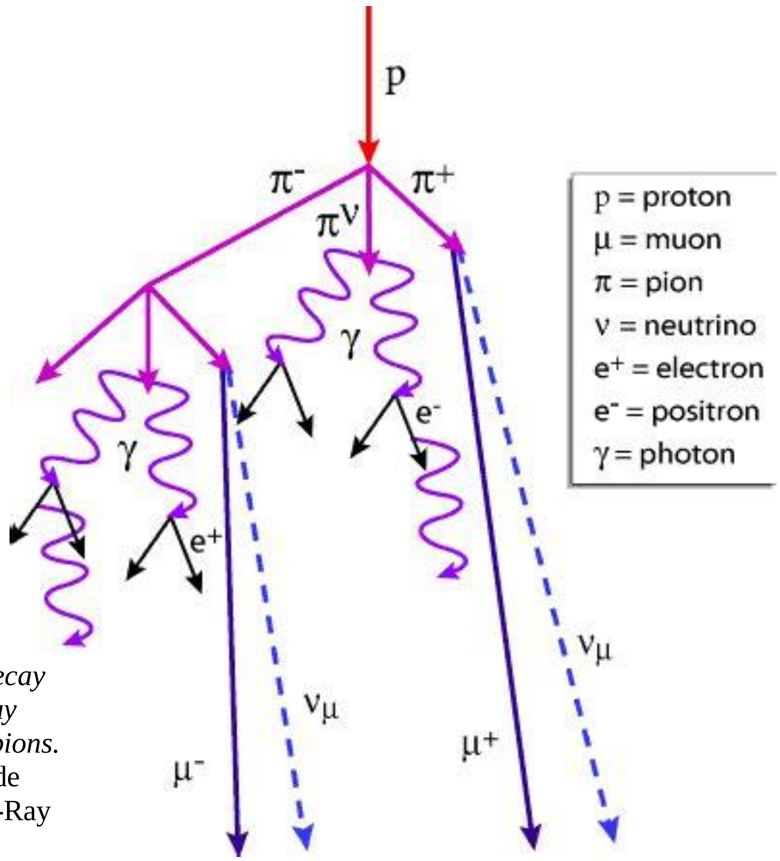

Figure 1 – A diagram showcasing the possible decay pathways after a cosmic ray particle has decayed into pions. (HAWK: The High-Altitude Water Cherenkov Gamma-Ray Observatory 2011)

Muon decay is mediated through weak interactions with other particles instead of strong or electromagnetic interactions (Beringer, et al. 2012). Due to this weak interaction and because muons have a relatively large mass, muons have fewer degrees of freedom to decay. This gives the particle a longer half-life than the pions initially created during cosmic showers. This also means that the muons produced during cosmic showers can gradually lose energy from interactions before decaying into secondary products. In addition, the muon's larger mass also means that the particle emits less radiation from deceleration, called bremsstrahlung radiation, during particle interactions, giving the muon the ability to penetrate further in matter than any other cosmic ray particle (Griffiths and Inglefield 1989). For this reason, muons have been recorded at Earth's surface and even below (Oláh, et al. 2013) .

Earth's atmosphere plays a pivotal role in sustaining life on the planet. Its chemical composition and density feed the planet's life cycle and protect it from potentially harmful radiation, including cosmic-ray muons. Earth's atmosphere consists of layers of gasses confined by Earth's gravitational pull. Atmospheric parameters will differ at different altitudes, including air composition, average temperature, and pressure.

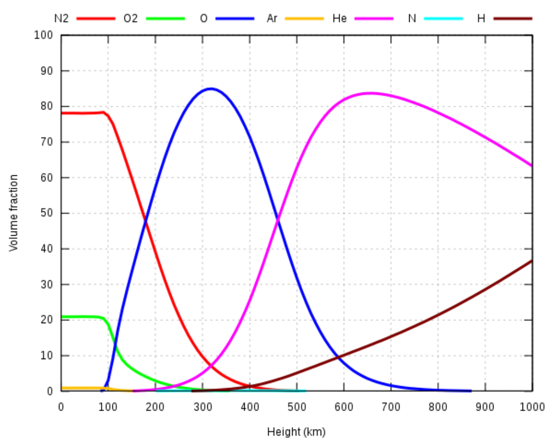

Figure 2 (top) – The volume fraction of the main constituents of the Earth's atmosphere as a function of height, based on the MSIS-E-90 atmospheric model (Community Coordinated Modelling Center n.d.).

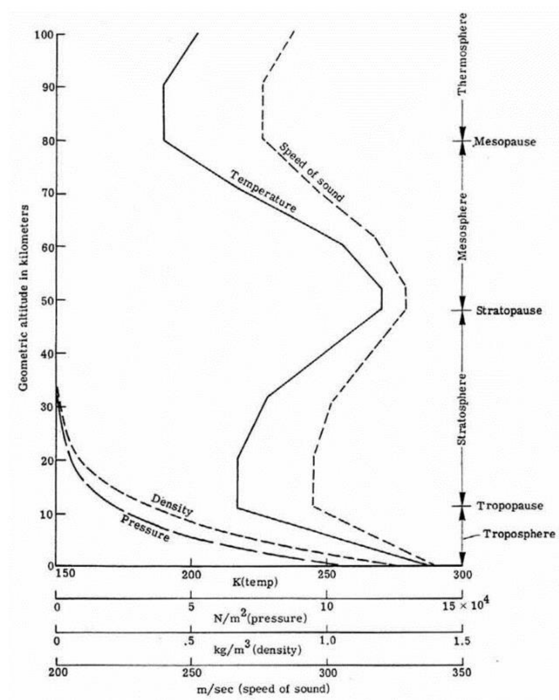

Figure 3 (right) - Geometric altitude vs. temperature, pressure, density, and the speed of sound derived from the 1962 U.S. Standard Atmosphere (NASA 1962).

Figures 2a and 2b show how these parameters differ on average based on altitude.

A common method of studying Earth's atmosphere is to launch an instrument payload on a weather balloon. Weather balloons are commonly synthetic rubber (neoprene) or latex and filled with helium or hydrogen. Historically, weather balloons and their payloads are designed to record and transmit atmospheric data for weather services. For example, the U.S. National Weather Service launches 92 balloons daily, and an estimated 900 balloons are launched worldwide daily for weather forecasting (NWS and NOAA n.d.). These balloons rise to upwards of 100,000 ft., travel several miles away, and are in the air an average of two hours.

Once a maximum altitude is reached, the pressure differential between the interior of the balloon and the surrounding atmospheric pressure will cause the balloon to rupture. A parachute attached to the balloon's payload will then take it safely to the ground to be retrieved. This maximum altitude of rupture and other flight parameters like ascent rate are determined based on factors including the type of balloon chosen, the chosen gas for the balloon, and the amount of gas the balloon is filled with. This gives the balloon operator the ability to roughly control the payload's flight based on mission requirements.

The atmospheric density changes with altitude and can be derived from the pressure and temperature. Due to the atmospheric attenuation, only high-energy particles can produce muon showers capable of reaching the surface of Earth. On the other hand, a detector at very high altitudes can detect more muons from lower energy cosmic rays, thus registering a higher muon rate. The central hypothesis behind Icarus I & II is that the muon production is expected to anticorrelate with the atmospheric pressure. A landmark study in 1934 tested a similar hypothesis showing an anticorrelation relationship between the cosmic ray flux gradient and altitude (Regener and Pfotzer 1934). Regener and Pfotzer found that the cosmic ray particle count rate gradually increased with increasing altitude, measured as atmospheric pressure in mm of mercury (Figure 3). This count rate shows a peak at 100 mm of mercury, representing just below where cosmic ray particles first interact with the matter in the atmosphere and cause these particle showers (see Figure 1). The Icarus missions were tasked with confirming these results using modern detection methods and collecting additional atmospheric data.

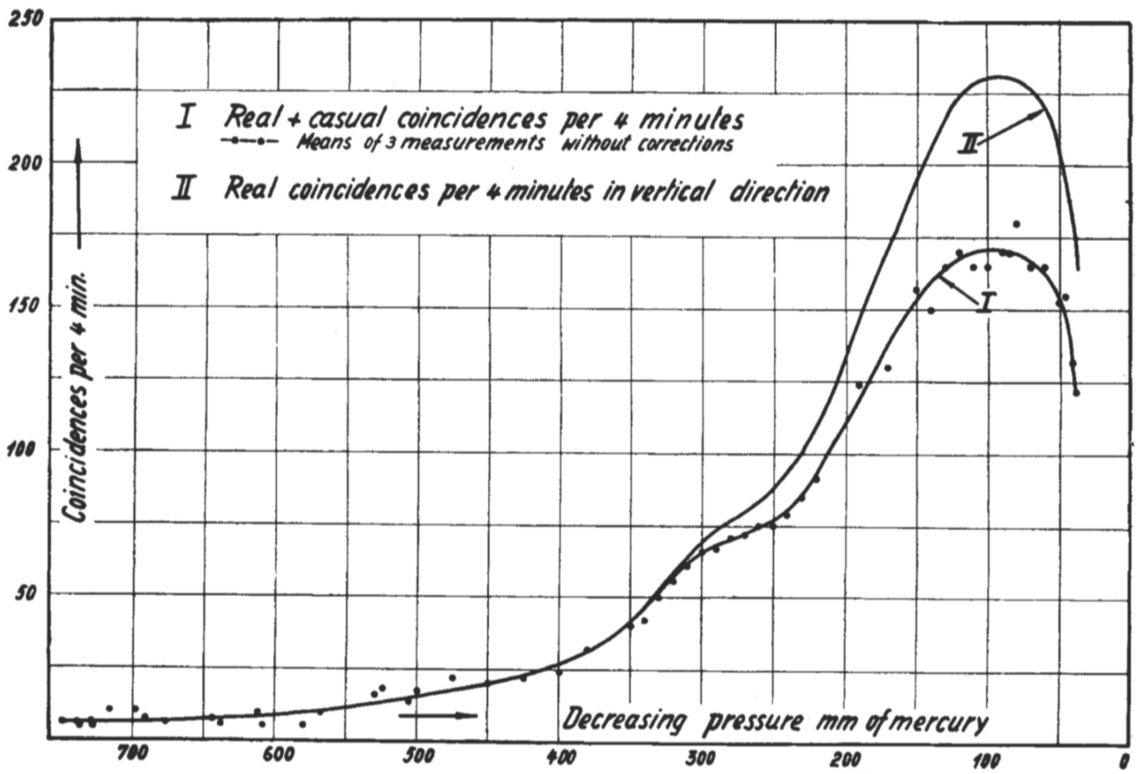

Figure 4 – Experimental results from Pfotzer et al. showing the rate of increase of cosmic ray particles as a function of atmospheric pressure (Regener and Pfotzer 1934).

II. METHODS

Both Icarus I and Icarus II were high-altitude balloon missions designed to carry a payload vertically through the atmosphere then be retrieved after it lands back down on Earth's surface. The methods used for these missions are broken into their own sections below.

Flight Design:

The Icarus balloon missions were designed to rise until a maximum altitude range. After that, the pressure difference between the inside and the atmosphere will cause the balloon to rupture. The Icarus payload then parachutes back down to the ground for retrieval. During every phase of its flight, the payload records the atmospheric muon gradient and atmospheric data, including temperature and pressure. This data is stored on memory cards for analysis after payload retrieval.

Along with the main scientific goals, the Icarus missions also served as catalysts for undergraduate student research involvement. With each balloon launch, the payload was optimized in design with the intention of future undergraduate students quickly implementing the design into their own high-altitude research projects. The Icarus missions were developed and launched under a new research-focused student organization at Texas State University named the Society for Space Exploration (SSE). SSE has been organized around developing and carrying out research missions, including high-altitude balloon missions.

Payload Design

The payload was designed to meet specific requirements of the Icarus missions. First, we needed a solid structure to house Icarus's sensors and electronics during flight. Second, this payload needed to meet a mass/volume ratio set by FAA guidelines requiring our structure to be made with a light yet durable material. Third, the payload structure is also needed to insulate the internals of Icarus from the cold temperatures of the upper atmosphere. Finally, due to the nature of the mission, the payload needed to withstand an impact after parachuting back down to the ground.

Due to these requirements, craft foam blocks were chosen for both Icarus missions because of the material's thermal and structural properties. Both Icarus payloads measured approximately 12x12x7.5 inches for their instrument casings. The added benefit of a foam casing is that the payload will float in the worst-case scenario of a water landing. Additionally, these blocks were sealed with tape for further insulation and structural support.

Figure 4 outlines each mission's complete layout. This includes the payload, a radar reflector for airplane traffic, a 5ft parachute for payload descent, and the weather

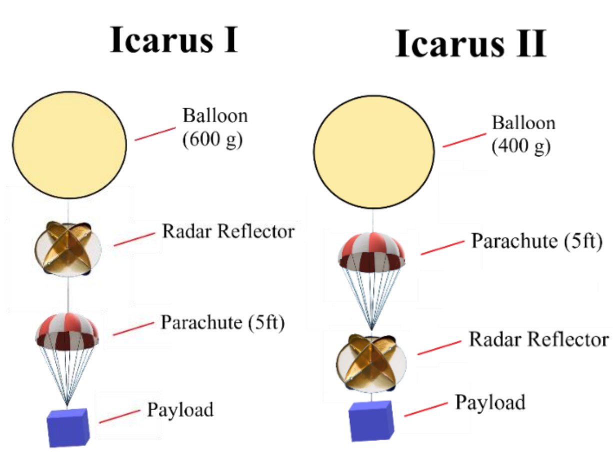

Figure 5 – Layout diagrams of both Icarus I and II. Icarus I included a larger balloon size (600 g) and its radar reflector was placed above the parachute. A smaller balloon size (400 g) was used for Icarus II and its radar reflector was moved to below the parachute to help prevent the parachute from not opening.

balloon itself. The only significant differences between the two layouts were the radar reflector placement and the smaller balloon size used for Icarus II. In addition, both missions used nylon rope and steel carabiners to connect each payload component to each other.

Figure 6 – Icarus II as it was found near Blanco, TX after parachuting to the ground from over 86,000 ft. in altitude.

Inside the payload of Icarus I, hand warmers were included to protect the mission's computer from the cold temperatures of the upper atmosphere. These hand warmers were not included in the Icarus II payload.

Muon Detector

An inexpensive device was built for the Icarus missions to detect the rate of muon interaction using a plastic scintillator and silicon photomultiplier (SiPM) (Axani 2018). The device works by absorbing part of the energy of a charged particle that passes through the scintillator and reemitting the energy as a photon. The SiPM can then detect the photon and convert it to an electrical signal based on many were recorded and at what time. In addition, through pulse amplification on the detector's circuit board and through coding in its processing unit, the detector can differentiate between muon interaction and the white noise produced through other particle or photon interactions. The detector keeps a total count of interactions and the wait time between these interactions giving an effective rate of muon interaction. The detector is also designed to record the energy levels of the muons passing through the scintillator.

The Icarus missions' main scientific instrument was a muon detector first designed by a team at MIT (Axani 2018). It was implemented and adapted into the Icarus instrument array for the Icarus scientific mission. The muon detector has four main parts: the silicon photomultiplier, a plastic scintillator block, a signal amplifier and processor, and a metal casing.

The plastic scintillator block absorbs the energy of a passing muon and reemits this energy as light through Coulomb interactions. An organic plastic scintillator was used, consisting of fluorescent material suspended in translucent plastic. The specific scintillator used on the Icarus missions consisted of a polystyrene base mixed with a primary dopant of 1% by-weight of POP (2,5-diphenyloxazole) and 0.03% secondary dopant POPOP (1,4-bis[2-(5-phenyloxazolyl)]benzene) (Beznosko, et al. 2004).

The light reemitted by the plastic scintillator is then detected by a silicon photomultiplier (SiPM). Photon detection enables us to extract information related to the incident particle by measuring the photon emission of a particle as it loses energy in a material. Photomultipliers are devices capable of producing a measurable electrical signal from the interaction of a single photon. Specifically, the photomultiplier used in the Icarus muon detector was silicone-based which has the advantage of operating at lower voltages than other photomultipliers while being compact. The SiPM was attached to the plastic scintillator with optical gel between the two components. Once the SiPM detects a photon being reemitted by the plastic scintillator, it sends an electrical signal through the detector's signal amplifier and processor.

The muon detector's signal amplifier and processor consist of a series of circuits designed to amplify the signal of a detected muon and comb out background noise from other sources, including gamma-rays and alpha particles. An analog-to-digital converter (ADC) makes the signal suitable for a microcontroller to record that data, including the event timestamp and the peak value from the ADC. The measured peak ADC value can then be converted back into a SiPM peak voltage, proportional to the number of photons incident on the SiPM, giving the effective energy of the incident muon. The Arduino Nano was chosen as the microcontroller for the muon detector for its compact size and low voltage requirements.

Atmospheric Sensor Array

In addition to the muon detector, both Icarus missions included a host of atmospheric and flight sensors for further data collection. Table 1 outlines what atmospheric and sensor data each mission was designed to collect. The main difference between Icarus I and II was the inclusion of a radiation detector in Icarus II for recording gamma radiation events during the mission's flight.

Atmospheric/Sensor Data Collection	Icarus I	Icarus II
Payload External/Internal Temperature	✓	✓
Atmospheric pressure	✓	✓
Gyroscope/Accelerometer Measurements	✓	✓
Date/Flight Time`	✓	✓
Gamma Radiation		✓

Table 1 – Atmospheric and sensor data that Icarus I and II were designed to collect respectively. Icarus II included the addition of a gamma ray detector.

For Icarus I, all sensors and instruments were controlled by a Raspberry Pi 3 Model B+. This is a Linux-based computer, and code for the instruments and sensors was written in python. However, this setup resulted in issues discussed further in the results section. Because of these issues, Icarus II operated on a collection of microcontrollers. A central microcontroller acted as the "master" data collection point for all sensors except the muon detector. The Arduino Mega was chosen for the master controller due to its large number of pins for connecting sensors and ample flash memory for the extensive code.

For Icarus II, the muon detector was separate from all other sensors. This separation was done for two reasons. First, the code necessary for the detector's operation would have caused stability issues with the master Arduino Mega due to its limited flash memory. Secondly, the separation of the detector gave the mission an added level of safeguard that valuable data will be collected even if there is a failure in one of the microcontrollers. To have the separated data relate to each other, the sensor array and the muon detector included clock modules. These modules are accurate to a second and were synced together before the flight.

Payload Tracking

Both Icarus missions utilized an amateur radio system called Automatic Packet Reporting System (APRS) for tracking their payloads. A transmitter with a GPS antenna attached was included inside the Icarus payload. Every two minutes, the transmitter would send out the GPS coordinates of the payload through the APRS network. This data included polar coordinates, the altitude of the payload, and average velocity.

The main advantage of the APRS network is that it isn’t reliant on the user to be the primary receiver. Instead, any signal using the APRS frequency and modulation will be uploaded to a central online database whenever received by any local radio operators with the proper setup. This gave us the ability to track the Icarus payloads even when out of range of our transmitter.

III. RESULTS

Icarus I & II were launched and retrieved successfully in August 2020 and April 2021, respectively. Icarus I was treated as a proof of concept for our balloon tracking and retrieval. Due to instrumental errors, no atmospheric data or muon flux gradient data was recorded on this mission. Icarus II, however, recorded both atmospheric and muon flux gradient data during most of its flight. The following section discusses the data collected during the Icarus II mission.

Icarus II's flight lasted approximately three hours. It reached an altitude of about 87,000 ft. before its balloon ruptured and parachuted to the ground approximately 30 miles from its launch site. Data was collected for the first hour and twenty minutes of the payload's flight before an instrumentation failure prevented further data collection. This data represents the atmospheric pressure range of about 910-250 hpa. and an approximate altitude range of 500-12,000 meters.

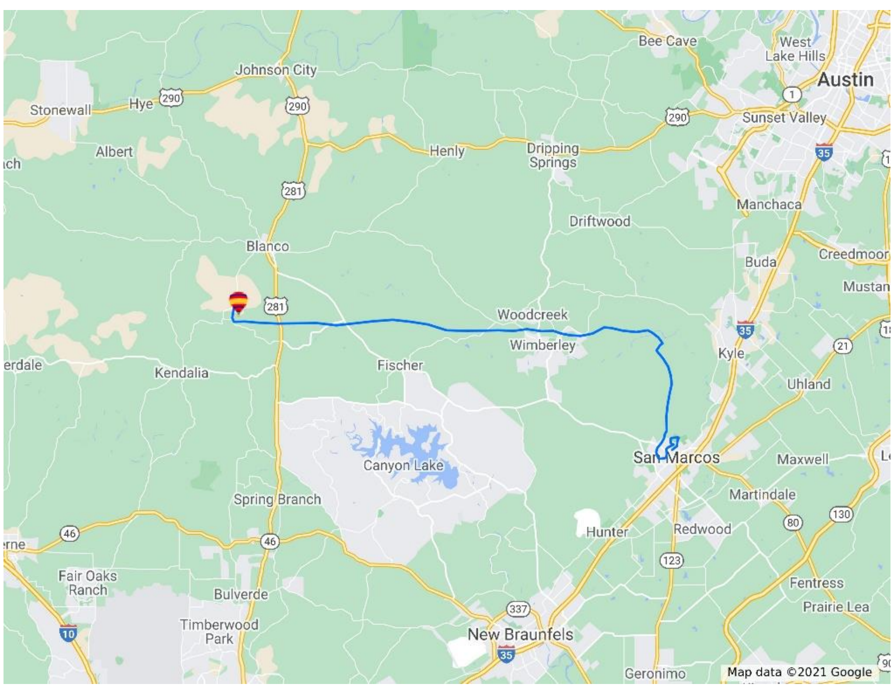

Figure 7 – Flight path of Icarus II. The launch location was at the Texas State University campus in San Marcos, TX. The payload landed just South of Blanco, TX approximately 3 hr. after launch.

Though the Pfotzer curve (Figure 3) measured cosmic ray coincidences per four minutes, the muon flux gradient measured by Icarus II can show a similar result to the 1934 study. Figure 7 shows the quadratic increase of the total number of muons detected with decreasing atmospheric pressure. This represents a higher rate of muon interactions at higher altitudes. This rate of muon interaction is further shown in Figure 8, which compares the rate of muon interactions with atmospheric pressure. At higher altitudes, the muon rate is higher than on the ground. Figure 8 also shows the peak of muon rate interaction representing the point in altitude where the most muons are first created from the decaying of their parent particles.

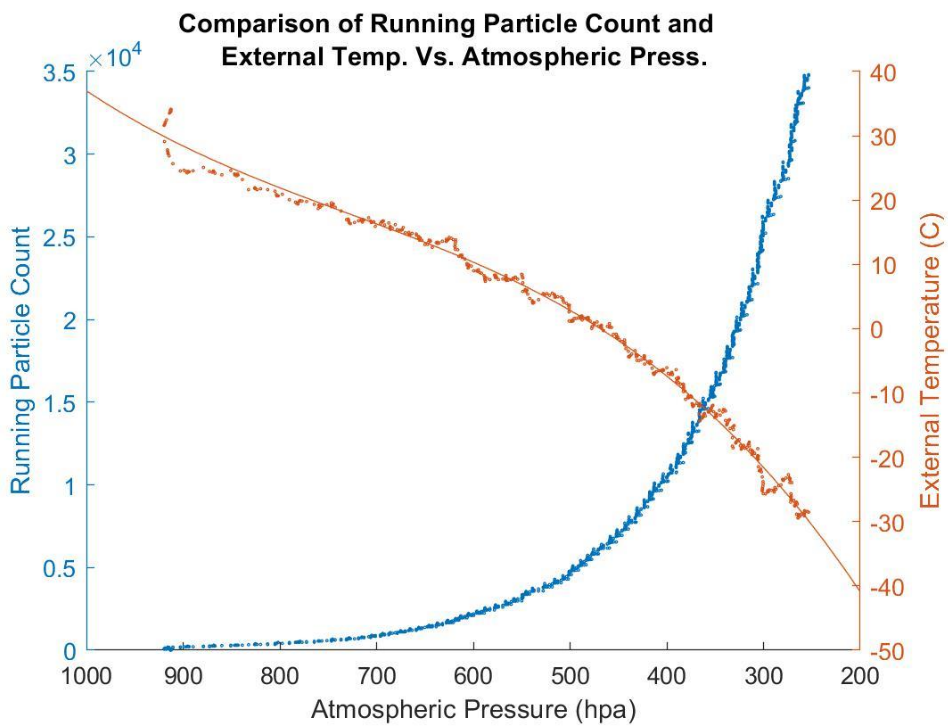

Figure 8 – The quadratic increase in the running total count of muon interactions with the muon detector compared with the atmospheric pressure and external temperature. This quadratic increase in muon count with decreasing atmospheric pressure represents a higher rate of muon interactions at higher altitudes.

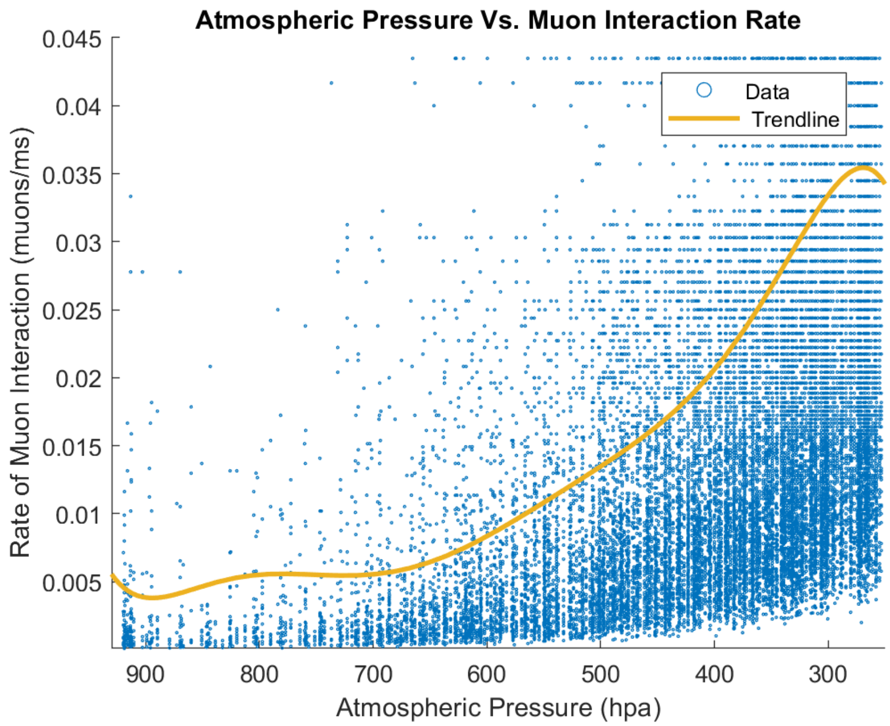

Figure 9 – The change in time (delta time) between muon interactions with the muon detector as a function of atmospheric pressure. At higher altitudes, the muon interaction rate is higher than lower altitudes.

Figure 9 shows a relationship between the SiPM voltage recorded for each muon interaction and the atmospheric pressure. This SiPM voltage indicates the energy each muon incident on the detector possesses. At higher altitudes, the muons that are incident on the detector are on average higher energy than those at lower altitudes. This is to be expected. As muons interact with matter in the atmosphere, they may lose energy before entirely decaying into secondary products. Thus, any muon detected at the surface of Earth may have once been a higher energy muon that lost a portion of its energy as it traveled through the atmosphere.

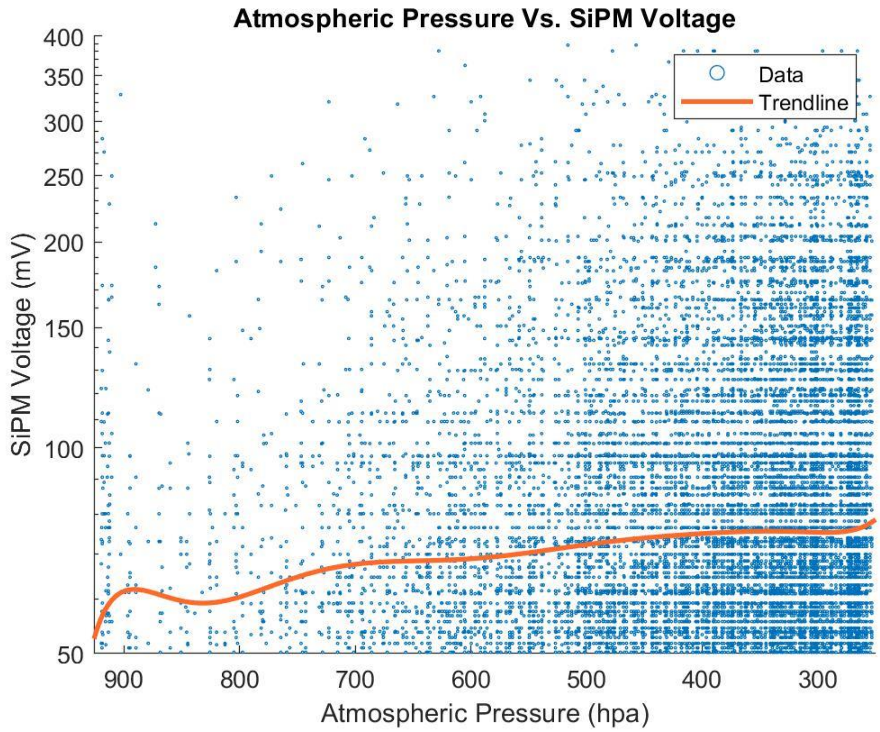

Figure 10 – SiPM voltage recorded for each muon interaction compared with the atmospheric pressure that the interaction occurred. The SiPM voltage can represent the relative energy of the incident muon. There are higher energy muons at higher altitudes than lower altitudes.

IV. CONCLUSION AND FUTURE PLANS

Both Icarus I and II were high altitude balloon missions designed under the student organization the Society for Space Exploration at Texas State University. These missions aimed to study the muon flux gradient in Earth's atmosphere and provide undergraduate research experience to the students at Texas State. Both missions were launched and retrieved successfully while Icarus II recorded the muon flux gradient during the payload's ascent and other atmospheric parameters.

Data collected during Icarus II shows a clear relationship between the atmospheric pressure and the muon flux. At higher altitudes, the rate of muon interactions is far more than at the surface of Earth. Moreover, muons incident at higher altitudes have higher energies than those at lower altitudes. This energy and altitude relationship shows the gradient nature of the muon flux resulting from cosmic showers. As muons travel further through our atmosphere, they will continually lose energy before decaying into secondary products. Thus, though the muons recorded at the surface of Earth may be of lesser energy, they most likely started as high-energy particles higher in the atmosphere. Icarus II shows a similar rate increase of cosmic rays to previous studies (Pfotzer et al. 1934).

It's essential to include commentary on the issues faced during both missions, including the instrumentational failures. This commentary serves to help any future research groups who may want to implement our methods in their own high-altitude research missions.

Icarus I's main computational power and data collection were designed around the Raspberry Pi 3 Model B+. This is an inexpensive, Linux-based computer that can run programs using python or C/C++ languages. This Instrumentational setup has several advantages and disadvantages to consider for high-altitude balloon missions. The Raspberry Pi was chosen for Icarus I due to its low cost, relatively low power consumption, and robust computational power. Icarus I had its entire atmospheric sensor array, including the muon detector, connected to a single Raspberry Pi computer where python scripts would operate these sensors and organize the collected data.

Shortly after its launch, the Raspberry Pi on Icarus I stopped recording data. Upon retrieving the payload after it landed, we noticed heat damage on the computer's circuits. We hypothesize that the combination of the hand warmers in the mission's payload and the high temperature of the Texas Summer day when the mission was launched caused the computer to overheat. This would have been exacerbated by the thermal regulation of the craft foam that the payload was comprised of. Because of this, hand warmers were not included in the payload of Icarus II, and these issues were not seen in this next mission.

Though Icarus II collected data for a significant portion of its flight, it ended this collection sooner than expected. This may be due to one of the limits of using a microcontroller for the central processor unit in a sensor array. Though the Arduino Mega has the largest amount of flash memory than any other microcontroller in the Arduino lineup, it is still less than the memory provided on a Raspberry Pi 3 Model B+. This lack of flash memory constrained the code written for controlling the mission's sensor array and may have been the cause of a computational error that stopped data collection during the mission's flight. To counter memory restrictions, microcontrollers may be connected in varying master-slave setups to distribute the flash memory burden among more microcontrollers. This, however, will increase power consumption for the mission's sensor array, so a balance must be met based on mission limits.

Along with their scientific goals, Icarus I and II also served an educational purpose. SSE is a student-operated research-focused organization whose primary purpose is to increase undergraduate research in space exploration at Texas State University. Both Icarus missions were developed and launched under SSE and acted as catalysts for undergraduate student research involvement. With each successive balloon launch, the payload design is optimized for quicker and easier development so future students in SSE may more easily implement their own high-altitude research missions using this framework.

To date, SSE has launched three high-altitude balloon missions, including Icarus I and II. A fourth mission is currently in development, with an estimated launch in early 2022. For future missions, several payload improvements are being considered. Firstly, an integrated PCB can be designed to connect sensors more easily to a central processing unit and have these connections be more secure during payload flight and landing. These PCBs may also be printed in large quantities at low cost to help with future high-altitude missions. Another improvement is to design a payload casing tailored to the atmospheric sensors being used. This will also reduce the possible errors in the vibrations experienced during balloon flight and optimize the space available for future scientific experiments.

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