A Cosmic Ray Particle Detector
High Altitude Balloon Payload

1 Synopsis

Cosmic ray muons produced in the upper atmosphere constantly rain down on the surface of the Earth. Here we propose to measure the flux (number of muons per unit area per second) as a function of altitude. The recent availability of silicon photomultipliers (SiPMs) allows one to do this using a low-mass detector that is simple, inexpensive, and robust. Data acquired by the detector and balloon tracking data will be transmitted to the ground and will be logged on board the balloon. The data thus acquired will be used to confirm the phenomenon of dilation predicted by Einstein's Special Theory of Relativity and to test models of cosmic ray production in the stratosphere.

These notes present a rough outline of a possible design for a suitable system. The project is ideally suited to student participation in that though the work is challenging, there are no overly steep learning curves involved. Moreover, the needed parts are readily available on a time scale compatible with a single-semester effort. Finally, there are multiple aspects to the design, which makes the project amenable to teamwork.

2 Background

The muon, which is a heavy cousin of the electron, is one of the basic building blocks of matter. Unlike the electron, which is stable, the muon decays with a mean life of 2.2 μs. Apart from cosmic rays, muons are therefore generally not encountered in nature, although they are copiously produced at particle accelerators.

Cosmic-ray muons are produced in the upper atmosphere as secondary byproducts of the interaction of galactic cosmic rays (mostly protons) that permeate insterstellar space. Most of the proton collisions take place at altitudes well above 3000 m. A naive (and incorrect!) estimate of the mean free path of a muon thus created is

$$\lambda = c\tau = 3 \times 10^{8}\ \text{m/s} \times 2.2 \times 10^{-6}\ \text{s} = 660\ \text{m}. \tag{1}$$

Taking this estimate at face value, one would conclude that the number of muons created in the upper atmosphere is enormous. Or, equivalently, that the muon flux should increase rapidly as one goes to higher altitudes. The muon flux at the surface of the Earth is roughly

$F_0 = 150\ \mathrm{s^{-1}m^{-2}}$. Scaling using the mean free path from Eq. 1, one would conclude that the muon flux at $h = 10,000$ m (the altitude of a commercial airliner) would be

$$F_{10\mathrm{km}} = N_0 \exp \frac{h}{\lambda} \simeq 6 \times 10^8\ \mathrm{s^{-1}m^{-2}}, \tag{2}$$

a prohibitively high radiation level.

The flaw in the analysis above is that it fails to take into account the time dilation effect predicted by the theory of special relativity. In particular, the muon's clock appears to tick more slowly by a factor of $\gamma = E_\mu/m_\mu \simeq 10$. Given that the typical energy of the cosmic ray muons is $E_\mu = 1$ GeV, the scaling factor becomes

$$F_{10\mathrm{km}} = N_0 \exp \frac{h}{\gamma\lambda} \simeq 680\ \mathrm{s^{-1}m^{-2}}. \tag{3}$$

The increase over the sea-level count rate is significant, but nowhere near the huge increase predicted without taking into account special relativity. This effect was dramatically demonstrated in the early 1960's, by Frisch and Smith, who measured the muon rate both at sea level and at the summit of Mount Washington in New Hampshire (elevation 1900 m).

Beyond demonstrating relativistic time dilation, measurements of the cosmic-ray rate as a function of altitude are of interest when it comes to testing models of muon production in the upper atmosphere. For example, the count rate from cosmic rays increases with increasing height to an altitude of $h = 20$ km, at which point it turns over and begins to fall. The simple detector proposed here will be capable of measuring the cosmic ray rate, but will not provide much additional information. More elaborate detectors in follow-on missions might, however, be capable of garnering information on the type of particles being detected, which would be of further interest.

3 System Overview

A conceptual block diagram of a possible system is shown in Fig. 1. Although Fig. 1 captures much of the needed functionality, several items need to be worked out. Key among them is the choice of microcontroller and communication link. Temperature control of the payload is another possible issue.

3.1 Particle Detector

The particle detector consists of a $7.5 \times 7.5 \times 0.6\ \mathrm{cm}^3$ slab of plastic scintillator, viewed by a $6 \times 6\ \mathrm{mm}^2$ SiPM. The SiPM is attached to the surface of the scintillator with optical cement.

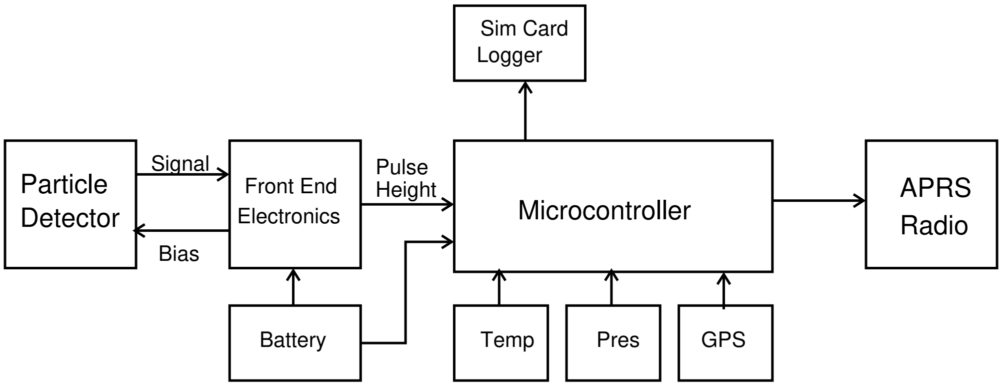

Figure 1: Conceptual block diagram of particle detector payload.

The MIT "Cosmic Watch" design (see `http://www.cosmicwatch.lns.mit.edu/about`) is an excellent starting point for the design, although modifications will be needed for the balloon-borne application.

Plastic scintillator is basically clear plastic (Polyvinyltoluene) that is doped with chemicals that produce a fast pulse of light in response to ionizing radiation. The sides of the plastic are optically smooth so that much of the light is trapped inside of the scintillator by total internal reflection. Light produced in the scintillator ricochets around until it encounters the part of the surface covered by the SiPM. The process just described is lossy, but the 5-10% of the initial light that enters the SiPM is sufficient to produce a useful signal.

To function properly, the SiPM must be "biased" to approximately 29 V. This is accomplished using a DC-DC converter on the Front End electronics board. Signals from the SiPM are amplified and then routed to a peak-detector circuit that holds them at a high level long enough for the analog-to-digital converter that is incorporated in the microcontroller to convert the size of the voltage pulse to a digital value. The pulse height and the time of the pulse are then recorded to a SIM card memory and/or sent to the ground using the communication link.

3.2 Tracking and Data Relay

Most high altitude balloon missions incorporate GPS tracking information that is relayed to the ground over radio links. Various solutions are available and the choice of system is open to discussion. Here we focus on the Automatic Packet Reporting System (APRS) which receives and relays small packets of digital data, is run by amateur ("ham") radio operators (see URL: `https://en.wikipedia.org/wiki/Automatic_Packet_Reporting_System`.

Most messages involve GPS data, but other messages are possible. In the case at hand, a summary of the number of detector counts would be transmitted. The APRS network comprises a set of radio stations, called digipeaters, that receive packets and rebroadcast them. Some of the nodes are Internet Gateways, which route the received data to the an internet backbone, where they are made available through an APRS server. This system allows data to be transmitted from the balloon to the ground, where they can be logged for future analysis.

Various options for APRS tracking hardware exist. The LightAPRS (URL: `http://qrp-labs.com/lightaprs` from QRP Labs is a promising possibility. This system is open source and features I2C and SPI interface pins that can be used to acquire data from the particle detector.

4 Present Status and Future Steps

At this writing, four suitably sized pieces of plastic scintillator have been ordered, with delivery anticipated in late February. SiPMs have also been ordered, as have a set of Cosmic Watch printed circuit boards and the associated parts. Although the Cosmic Watch boards may not be directly suitable for the balloon payload, at the very least they will provide for a quick start in terms of early testing of the scintillation detectors.

A general concept for a partical detector payload is established, but several design choices remain to be made. In addition there is the work of actual fabrication and integration of the full balloon system. A partial list of tasks includes:

1. Construct and test particle detector using Cosmic Watch readout scheme.
2. Decide on a scheme for tracking. Select radio hardware and fix interface strategy.
3. Design a modified version of the particle detection front end board that is more directly compatible with the chosen APRS (or other) communication system.
4. Test APRS system on ground.
5. Design and build a power system.
6. Design and fabricate a mechanical package.
7. Plan mission (choice of balloon, launch site, launch date, etc.)