

Space Weather

FEATURE ARTICLE

10.1002/2016SW001410

Special Section:

Initial Results from the NASA
Radiation Dosimetry
Experiment (RaD-X) Balloon
Flight Mission

Citation:

Phillips, T., et al. (2016), Space Weather
Ballooning, *Space Weather*, 14, 697–703,
doi:10.1002/2016SW001410.

Published online 22 OCT 2016

Space Weather Ballooning

Tony Phillips, Sam Johnson, Amelia Koske-Phillips, Michael White, Amelia Yarborough, Aaron Lamb, Anna Herbst, Ferris Molina, Justin Gilpin, Olivia Grah, Ginger Perez, Carson Reid, Joey Harvey, and Jamie Schultz

Abstract We have developed a “Space Weather Buoy” for measuring upper atmospheric radiation from cosmic rays and solar storms. The Buoy, which is carried to the stratosphere by helium balloons, is relatively inexpensive and uses off-the-shelf technology accessible to small colleges and high schools. Using this device, we have measured two Forbush Decreases and a small surge in atmospheric radiation during the St. Patrick’s Day geomagnetic storm of March 2015.

Introduction

Space is not far away. Only 30 km above Earth’s surface—less than the length of a marathon race—the blue sky fades to black and stars pop out in broad daylight. At such altitudes, the ambient temperature (as low as -70°C), air pressure ($<1\%$ sea level), and cosmic radiation environment are akin to the planet Mars.

In 2011, a group of student researchers in Bishop, California, began launching suborbital helium balloons [Larson *et al.*, 2009] to explore this near-space environment. Their organization, “Earth to Sky Calculus,” has since flown more than 140 missions to the stratosphere for a fraction of the cost of traditional space missions. Many of the flights have tested technologies for a “Space Weather Buoy” to measure cosmic rays and the response of the upper atmosphere to solar storms. These experiments are part of the overall space weather community’s “Citizen Science” efforts [Knipp, 2015].

The Buoy is now fully developed and, in this paper, we report findings from flights in 2014 and 2015. Key results include the detection of two Forbush Decreases in 2014 and a surge in upper atmospheric radiation during the St. Patrick’s Day Storm of March 2015. The technology of the Buoy is affordable and accessible to high schools and small colleges and could form the basis for a continental network of space weather balloon programs.

Materials and Methods

The Payload

The Space Weather Buoy is a lunch box-sized payload that can measure temperature, ionizing radiation, and GPS altitude from sea level to more than 35 km. The payload ascends to the stratosphere, carried by a helium-filled balloon, and descends by parachute after the balloon pops.

The payload weighs approximately 2 kg. It is not only “lunch box sized,” it actually is an insulated lunch box (CoolCellTM), which provides $+30^{\circ}\text{C}$ of thermal protection to the interior. Instrumentation is mounted on both the interior and exterior surfaces of the container.

The following instruments are mounted on the payload:

1. Polimaster PM1621M radiation sensor: This device, mounted inside, senses X-rays and gamma rays in the energy range 10 keV to 20 MeV. Early versions of the Space Weather Buoy carried only one PM1621M. We now routinely fly four of the devices for redundancy and to improve the signal-to-noise ratio of our measurements. Each sensor contains a data logger, which records dose rates in units of microGy/h every minute during the flight. (cost per sensor is \$900).
2. TinyTag TV-4204 cryogenic thermometer: This device consists of a metal probe, mounted outside the payload, and a temperature logger, mounted inside, that records the exterior temperature every 1 s during the flight (\$250).
3. SPOT Trackers: Two standard GPS hiking trackers are mounted on orthogonal faces of the payload’s exterior. They provide coordinates as often as every 2 min during the balloon’s flight, which we monitor in real time using SPOT LLC’s online interface (<http://findmespot.com>). When the balloon parachutes back to Earth, signals from the SPOT trackers guide us to the landing site. The orthogonal mounting of the trackers insures that no more than one tracker can land facedown in the dirt (\$150 per tracker).

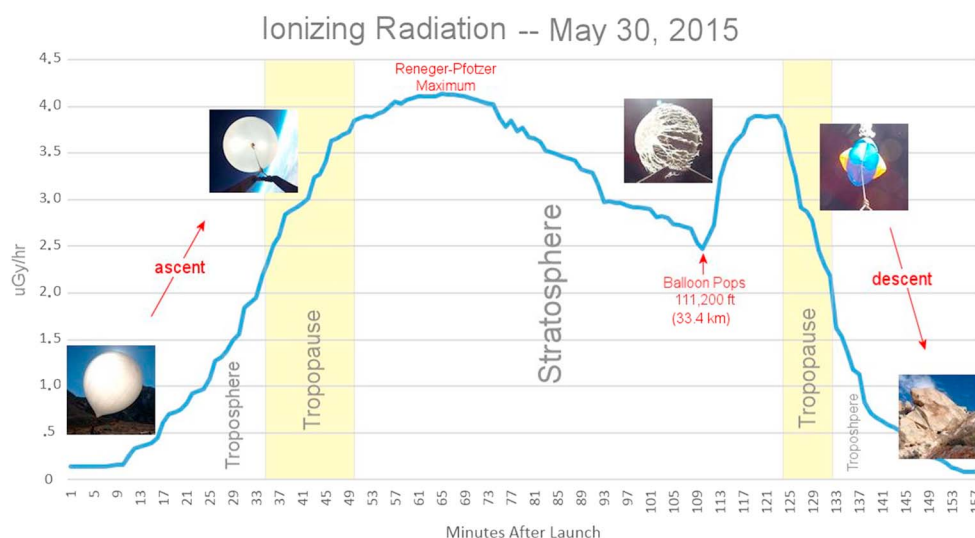


Figure 1. Ionizing radiation dose rates measured during a 30 May 2015 flight of an Earth to Sky Calculus “Space Weather Buoy.” The curve is an average of data collected by four identical PM1621 radiation sensors, which respond to X-rays and gamma rays in the energy range 10 keV to 20 MeV.

4. GPS altimeter #1: Mounted to the outside of the payload, a rugged Garman eTrex20 GPS tracker records the balloon’s 3-D coordinates every 10 s during the flight up to altitudes as high as 30 km (\$200).
5. GPS altimeter #2: A recent addition to the payload, this experimental altimeter, based on the Arduino MEGA microprocessor, records the balloon’s 3-D coordinates every 1 s during the flight up to altitudes as high as 56 km. The circuitry of device is mounted inside the payload bay; the antenna is mounted outside (\$200).
6. Video cameras: Two GoPro Hero3+ video cameras are mounted inside the payload, looking out of camera bays to film the sky and landscape during the flight. A typical flight produces 64 GB of HD video (\$500 per camera).

The total cost of this payload is \$5550. It is relatively easy to assemble and is regularly launched by high school teams unassisted by adults.

Launch and Landing

We use a 1600 g natural rubber balloon inflated with 5.7 cubic meters (200 cubic feet) of helium. With a 2 kg payload, this balloon produces ascent rates near 5.5 m/s. The payload stack rises at this rate until the balloon explodes typically 32 km to 35 km above Earth’s surface. The balloon explodes because, as it rises, it attempts to maintain pressure equilibrium with its surroundings. Surrounded by increasingly thin air, the balloon expands to reduce the pressure and density of the helium. Eventually, the fabric of the balloon reaches the limit of its elasticity. It can expand no further and pops. As the payload falls, a 2.5 m diameter parachute (of the type used for model rocketry) naturally fills with up-rushing air and slows the descent for a soft landing on the Earth below. Descent rates are typically near 7.5 m/s as the payload is approaching the ground.

The launch site where we release our balloons is located at an altitude of 2600 m in the Eastern Sierra mountain range near Bishop, California. Landing sites are typically located 10 km to 200 km away in the Death Valley National Park, the White Mountains, and the Inyo Mountain range of California.

Data: The Regener-Pfotzer Maximum

Figure 1 shows a sample profile of ionizing radiation collected during a 2.5 h flight to the stratosphere on 30 May 2015. The maximum altitude of the flight was 33.9 km.

Newcomers to the field of atmospheric radiation measurements often expect dose rates to peak at the apex of the flight. Instead, the peak occurs approximately halfway up, in the lower stratosphere. When cosmic rays crash into Earth’s atmosphere, they produce a spray of secondary particles. With increasing depth in the atmosphere, the primary cosmic radiation component decreases, whereas the secondary radiation

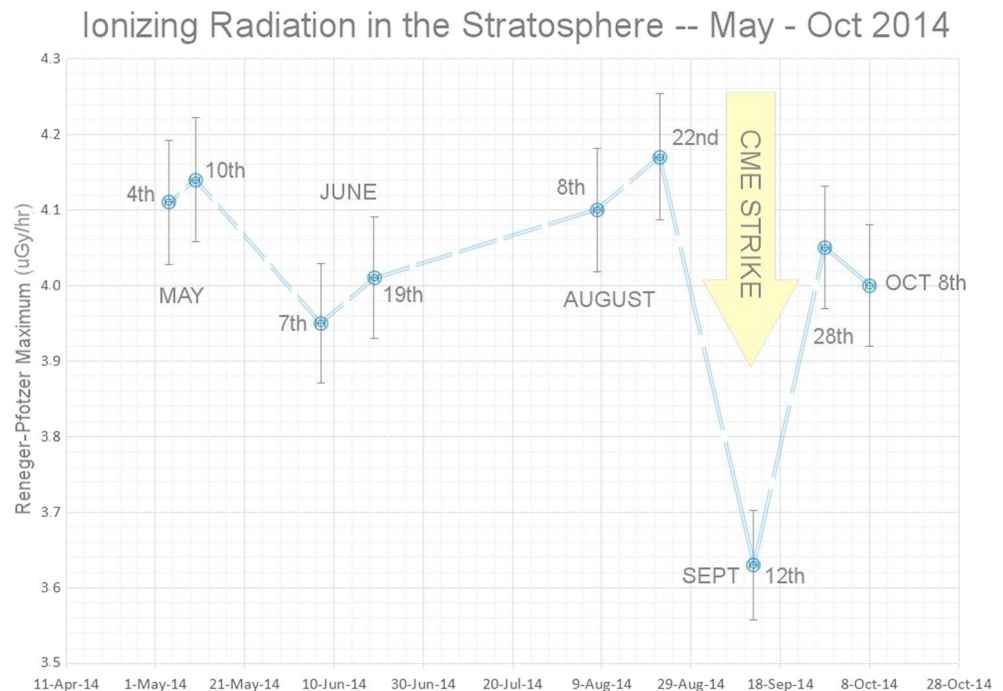


Figure 2. Each point in this plot shows the peak of the Regener-Pfotzer Maximum measured during a flight of Earth to Sky's Space Weather Buoy. Two-sigma error bars are estimated from the scatter of measurements by independent sensors on board each payload. Note that no measurements were actually made between the data points; the dashed lines are meant only as a guide for the eye and do not reveal variations that may be present in the data gaps. This statement is true for all subsequent plots of balloon data in this paper.

component increases. This situation results in a maximum dose rate at an altitude of ~ 20 km. This is often called the "Regener-Pfotzer maximum," named after physicist Erich Regener and his student George Pfotzer who discovered the peak using balloons and Geiger tubes in the 1930s [Carlson and Watson, 2014].

We have radiation profiles similar to this one on more than 50 dates between October 2013 and December 2015. This allows us to draw some conclusions about the average width and altitude of the Regener-Pfotzer Maximum over our launch site ($+37^\circ\text{N}$, -118°W) and to sample the stratosphere during multiple solar storms.

Because the Regener-Pfotzer Maximum is broad, our balloons spend a significant amount of time inside it, typically 50 min or more per flight. This gives us long integration times and high signal-to-noise ratios. The peak of each Regener-Pfotzer Maximum is found by fitting a simple parabolic curve to 1 min averaged data. Typical values are near 4 uGy/h with statistical uncertainties of order 1%. The average width of the Regener-Pfotzer Maximum, defined as the full width at 90% of the peak, is $7.8 \text{ km} \pm 0.8 \text{ km}$. The average altitude of the peak is $20.4 \text{ km} \pm 0.4 \text{ km}$. These values apply to the standard range of latitude and longitude for our balloon flights, between 36.5°N and 37.5°N , and between -117°W and -118°W . The quoted uncertainties are 2 standard deviations wide.

Results

The goal of our monitoring program is to detect changes in the upper atmosphere in response to solar activity. We have succeeded on three occasions, summarized below.

Two Forbush Decreases

The first case was 12 September 2014. A pair of coronal mass ejections (CMEs) hit Earth's magnetic field, sparking a G3-class ($K_p=7$) geomagnetic storm [Spaceweather.com, 2014a; U.S. Geological Survey, 2014]. We launched a balloon during the peak of the storm, naively expecting to observe an increase in ionizing radiation compared to earlier flights during quiet conditions. Instead, we detected a sharp decrease, shown in Figure 2.

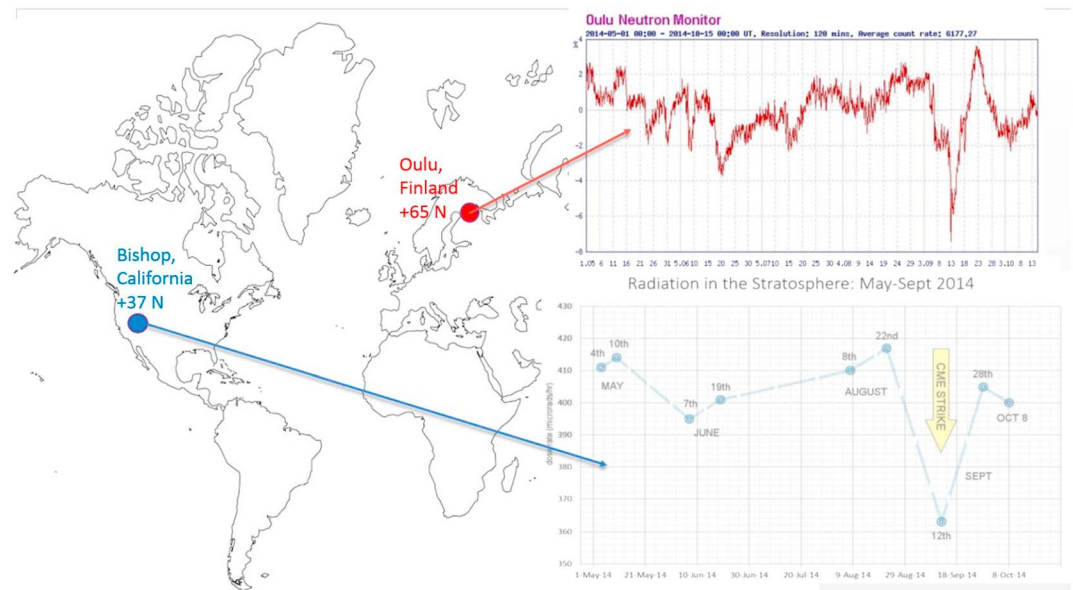


Figure 3. Ionizing radiation measurements in the stratosphere over California (below) compared to ground-level neutron counts from Oulu, Finland (above). The quiet-time averaging period for the Oulu data is 6 months. Qualitatively, the two data sets are in good accord despite wide differences in altitude and latitude.

This effect is called a “Forbush Decrease,” named after physicist Scott E. Forbush who first described it in the twentieth century [Forbush, 1938]. Magnetic fields in the CMEs scattered cosmic rays away from Earth, causing a decrease in the peak of the Regener-Pfotzer Maximum. The peak on 12 September dropped approximately 9% compared to flights before and after 12 September 2014.

This Forbush Decrease was also observed by neutron monitors around the world such as the Oulu Cosmic Ray Station in Finland [Usoskin et al., 2009] and the global network of stations operated by the Bartol Research Institute [Kuwabara et al., 2006]. Ground-level neutron counts are considered to be a good proxy for cosmic rays. The timing and magnitude of the Forbush Decrease we measured in the stratosphere over California were in good accord with ground-level neutron data. As an example, Figure 3 compares our data to those of Oulu.

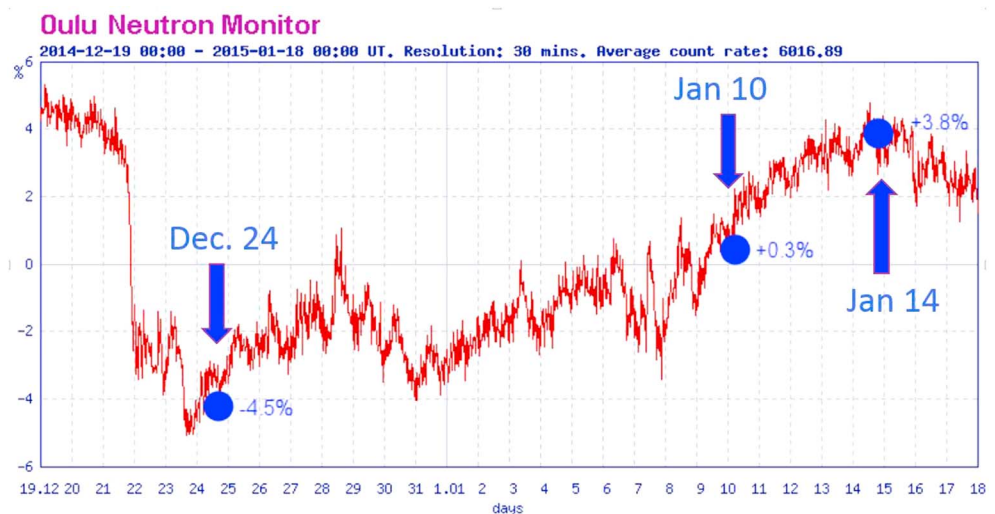


Figure 4. The slow Forbush Decrease of December 2014 to January 2015. The red curve traces neutron counts from the Cosmic Ray Station at Oulu, Finland. The blue dots are measurements of the Pfotzer Maximum in the stratosphere over California. To make a comparison possible, both data sets are expressed as a percentage change with respect to a long-term average (1 month for the neutron data and 6 months for the comparatively sparse balloon data).

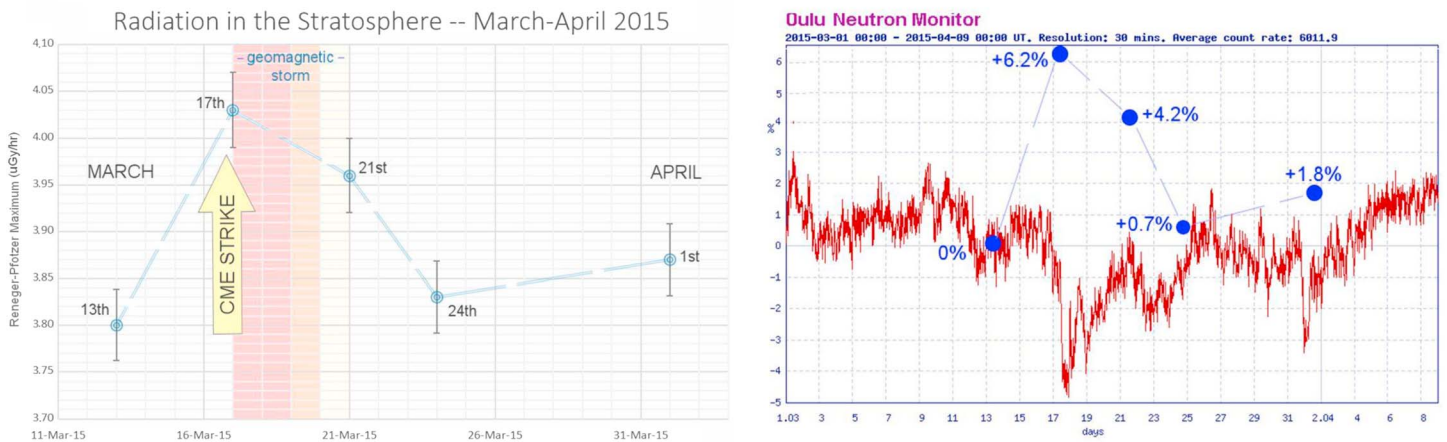


Figure 5. (a) The peak of the Regener-Pfotzer Maximum over central California increased in intensity during the St. Patrick's Day geomagnetic storm of 2015. Error bars are estimated from the scatter of measurements by independent sensors on board each payload. (b) The radiation event of March 2015. Red curve traces neutron counts from the Cosmic Ray Station at Oulu, Finland. Blue dots are our measurements of the Regener-Pfotzer Maximum in the stratosphere over California. To make a comparison possible, both data sets are expressed as a percentage change with respect to a long-term average (1 month for the neutron data and 6 months for the relatively sparse balloon data).

We observed another Forbush Decrease in late December 2014. On 21–22 December, a pair of CMEs delivered glancing blows to Earth's magnetic field. The result was a minor G1-class ($Kp = 5$) geomagnetic storm [Spaceweather.com, 2014b]. The geomagnetic storm subsided in a matter of hours, but the associated Forbush Decrease lasted for nearly 1 month. Figure 4 shows neutron counts from Oulu, Finland.

During this slowly evolving event, we launched three balloons on 24 December 2015, 10 January 2015, and 14 January 2015. Blue dots in Figure 4 denote the peak of the Regener-Pfotzer Maximum, which we measured in the stratosphere, expressed as a percentage of the 2014 annual average.

For this particular event, balloon data were tightly correlated with the Oulu neutron counts—even more so than during the 12 September Forbush Decrease. The degree of correlation is remarkable given the geographic separation between observing sites and the fact that the two data sets represent such different ways of sampling the cosmic ray environment.

Forbush decreases are well known to exhibit a wide range of recovery times depending on the structure and magnetic turbulence of the CMEs that caused them [Penna and Quillen, 2005; Aly, 2013]. Both of the Forbush decreases we observed were within the bounds of normal and gave us a chance to successfully sample both relatively fast- and slow-rebounding events.

Geomagnetic Storm

The third case occurred on 17 March 2015, when a CME struck Earth's magnetic field, triggering a severe G4-class ($Kp = 8$) geomagnetic storm, at the time (and still) the strongest geomagnetic storm of Solar Cycle 24 [Cherniak et al., 2015; Kamide and Kusano, 2015]. We explored the "St. Patrick's Day Storm" with a series of five balloon launches—one before the storm (13 March), one during the storm (17 March), and three after the storm (21 and 24 March and 1 April 2015).

Figure 5a shows the data from those five flights. Instead of a Forbush Decrease, we measured a sudden uptick in ionizing radiation.

On previous occasions when we measured a Forbush event, our data closely tracked polar neutron monitor counts. However, this was not so for the St. Patrick's Day Storm. Figure 5b compares our stratospheric balloon measurements to Oulu neutron counts. The two trends are opposite. The ground-level neutron monitor observed a decrease in radiation, while the balloons observed an increase.

This observation, while puzzling, might not be unprecedented [Brown, 1959]. In 1958, researchers led by Robert R. Brown at UC Berkeley launched a series of high-altitude balloons carrying Geiger counters to the stratosphere over central California. Their balloons, payloads, and flight profiles were remarkably similar to our own, especially considering the six-decade gap in time and technology. They also operated a neutron

monitor on the ground throughout the entire experiment. On two occasions, 17 April and 8 July 1958, they detected an excess of soft X radiation in the Regener-Pfotzer maximum during strong geomagnetic storms when auroras were sighted at latitudes as far south as 50°. While the neutron monitor registered a Forbush decrease, the balloons detected an X-ray increase—much the same as our measurement during the St. Patrick's Day storm of 2015. Brown discussed the possibility that the X-rays his balloons detected might have come from auroras [Winckler *et al.*, 1958; Stadsnes *et al.*, 1997; Halford *et al.*, 2015], which approached the launch site unusually close during the storms in question.

For now we offer no physical explanation for these puzzling observations. We do, however, suggest that they be taken seriously and investigated with additional balloon flights during future periods of extreme geomagnetic activity.

Conclusions

We have succeeded in measuring changes to the radiation environment of the stratosphere during three solar and geomagnetic storms. These data are of interest to atmospheric scientists, space weather forecasters, and entrepreneurs of space tourism who hope to build vessels to carry human passengers to the same altitudes as our balloons.

There is, however, room for improvement in our radiation payload. For one thing, it only samples a fraction of the total radiation environment. For example, our payload is completely insensitive to neutrons. Neutrons are a very important form of cosmic radiation, providing at least half of the biologically effective radiation dose at altitudes of interest to aviation and space tourism. To monitor this type of radiation, we are currently experimenting with bubble chambers and active neutron dosimeters that can fly successfully on board a small balloon payload.

We would also welcome collaboration with more senior groups who occasionally fly sophisticated radiation sensors on board research aircraft and heavy-lift balloons. Including our payload as a “hitchhiker” on such flights would allow a valuable cross calibration of our low-energy sensors with devices of greater sensitivity and spectral range.

Finally, we wish to form a “Space Weather Balloon” network, geographically distributed across North America and ultimately across the globe. Simultaneous launches of payloads like the one we have developed could reveal the 3-D response of the atmosphere to solar storms over wide areas, not just in a single flight path over California. Indeed, we have already started multipoint balloon launches with a pair of simultaneous California-New Hampshire flights in 2015 [Joyce *et al.*, 2016].

We have shown that it is possible to measure dynamics in upper atmospheric radiation using a relatively inexpensive payload for small helium balloons. The price point is within easy reach of many high schools and small colleges, and the technological know-how is not prohibitive. Most of the devices contained inside the lunch box payload are off the shelf and do not require advanced degrees in electrical engineering or radiation physics to operate.

Despite the relative simplicity of the payload—or perhaps because of it—Space Weather Buoys are able to make meaningful astrophysical measurements. In less than 1 year, we have detected changes in the stratosphere in response to three solar storms. In two cases (September and December 2014), Forbush Decreases in the stratosphere were well correlated with similar Forbush Decreases observed by neutron monitors on the ground. During the St. Patrick's Day Storm of 2015, however, ground measurements of neutrons and balloon measurements of ionizing radiation were almost perfectly anticorrelated. This shows that we have a lot to learn, and using our techniques, young scientists are fully capable of participating in this exciting research.

References

- Aly, N. (2013), The characteristics of Forbush decreases of cosmic ray intensity, *IJRRAS*, 15(3), 330–336.
- Brown, R. (1959), Excess radiation at the Pfotzer Maximum during geophysical disturbances, *J. Geophys. Res.*, 64, 328–329.
- Carlson, P., and A. A. Watson (2014), Erich Regener and the ionisation maximum of the atmosphere, *Hist. Geo Space Sci.*, 5, 175–182, doi:10.5194/hgss-5-175-2014.
- Cherniak, I., I. Zakharenkova, and R. J. Redmon (2015), Dynamics of the high-latitude ionospheric irregularities during the 17 March 2015 St. Patrick's Day storm: Ground-based GPS measurements, *Space Weather*, 13, 585–597, doi:10.1002/2015SW001237.

Acknowledgments

This research was crowd-funded by the readers of Spaceweather.com and individual sponsors of the Earth to Sky Calculus space weather ballooning program. Readers who wish to receive the data presented in this paper should send their requests to dr.tony.phillips@gmail.com. We also acknowledge data from the Oulu Cosmic Ray Station available online at <http://cosmicrays.oulu.fi/> maintained by the University of Oulu and Sodankylä Geophysical Observatory. The rapidly available data and online display tools at the Oulu website made it especially easy to explore the similarities and differences between balloon and neutron data. Finally, several CMEs and solar storms are referenced in this paper. Solar wind data at L1 for those events may be found at the Advanced Composition Explorer Science Center home page: <http://www.srl.caltech.edu/ACE/ASC/>.

- Forbush, S. E. (1938), On world-wide changes in cosmic-ray intensity, *Phys. Rev.*, **54**, 975–988, doi:10.1103/PhysRev.54.975.
- Halford, A. J., et al. (2015), BARREL observations of an ICME-shock impact with the magnetosphere and the resultant radiation belt electron loss, *J. Geophys. Res. Space Physics*, **120**, 2557–2570, doi:10.1002/2014JA020873.
- Joyce, C. J., et al. (2016), Atmospheric radiation modeling of galactic cosmic rays using LRO/CRaTER and the EMMREM model with comparisons to balloon and airline based measurements, *Space Weather*, **14**, doi:10.1002/2016SW001425.
- Kamide, Y., and K. Kusano (2015), No major solar flares but the largest geomagnetic storm in the present solar cycle, *Space Weather*, **13**, 365–367, doi:10.1002/2015SW001213.
- Knipp, D. J. (2015), Space weather and citizen science, *Space Weather*, **13**, 97–98, doi:10.1002/2015SW001167.
- Kuwabara, T., et al. (2006), Real-time cosmic ray monitoring system for space weather, *Space Weather*, **4**, S08001, doi:10.1029/2005SW000204.
- Larson, S. L., J. C. Armstrong, and W. A. Hiscock (2009), The first frontier: High altitude ballooning as a platform for student research experiences in science and engineering, *Am. J. Phys.*, **77**, 489, doi:10.1119/1.3097775.
- Penna, R. F., and A. C. Quillen (2005), Decay of interplanetary coronal mass ejections and Forbush decrease recovery times, *J. Geophys. Res.*, **110**, A09S05, doi:10.1029/2004JA010912.
- Spaceweather.com (2014a), The K7 geomagnetic storm of Sept 12, 2014. [Available at <http://spaceweather.com/archive.php?view=1&day=13&month=09&year=2014>.]
- Spaceweather.com (2014b), The K5 geomagnetic storm of Dec. 21–22, 2014. [Available at <http://spaceweather.com/archive.php?day=21&month=12&year=2014&view=view>.]
- Stadsnes, J., K. Aarsnes, and J. Boordal (1997), X-ray imaging of the aurora, *Adv. Space Res.*, **20**(4.5), 1043–1054.
- U.S. Geological Survey (2014), [Available at <http://geomag.usgs.gov/storm/21>.]
- Usoskin, I. G., E. Valtonen, R. Vainio, P. J. Tanskanen, and A. M. Aurela (2009), History of cosmic ray research in Finland, *Adv. Space Res.*, **44**, 1232–1236.
- Winckler, J. R., L. Petersen, R. Arnoldy, and R. Hoffman (1958), X-rays from visible aurorae at Minneapolis, *Phys. Rev.*, **110**, 1221–1231.

Tony Phillips is the author of *Spaceweather.com* located in the Sierra Nevada mountains of central California. E-mail: dr.tony.phillips@gmail.com

Sam Johnson is an undergraduate at Stanford University majoring in engineering.

Amelia Koske-Phillips is an undergraduate at the University of Oregon (Eugene, OR) majoring in Human Physiology.

Michael White is an undergraduate at UC Berkeley majoring in engineering.

Amelia Yarborough is a student member of Earth to Sky Calculus, taking a gap year before college to explore the stratosphere.

Midshipman Aaron Lamb is an undergraduate at the California State University Maritime Academy in Vallejo, CA, where he has started his own stratospheric ballooning group, "Earth to Sky Maritime."

Anna Herbst is an undergraduate at King's College, London, majoring in political economics.

Ferris Molina is a student member of Earth to Sky Calculus who is taking a gap year to write and publish his first novel.

Justin Gilpin is an undergraduate at UC San Diego where he studies chemical engineering.

Olivia Grah is an undergraduate at Princeton University in New Jersey.

Ginger Perez is an undergraduate at Santa Monica Community College in California.

Carson Reid is a student member of Earth to Sky Calculus currently taking a gap year to explore the stratosphere and the High Sierra.

Joey Harvey is an undergraduate at the University of California Irvine where he plans to major in Business.

Jamie Shultz is an undergraduate at California Lutheran University in Thousand Oaks, CA.