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Evolution of scientific ballooning and its impact on astrophysics research

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Abstract

As we celebrate the centennial year of the discovery of cosmic rays on a manned balloon, it seems appropriate to reflect on the evolution of ballooning and its scientific impact. Balloons have been used for scientific research since they were invented in France more than 200 years ago. Ballooning was revolutionized in 1950 with the introduction of the so-called natural shape balloon with integral load tapes. This basic design has been used with more or less continuously improved materials for scientific balloon flights for more than a half century, including long-duration balloon (LDB) flights around Antarctica for the past two decades. The U.S. National Aeronautics and Space Administration (NASA) is currently developing the next generation super-pressure balloon that would enable extended duration missions above 99.5% of the Earth's atmosphere at any latitude. The Astro2010 Decadal Survey report supports super-pressure balloon development and the giant step forward it offers with ultra-long-duration balloon (ULDB) flights at constant altitudes for about 100 days.

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Keywords: Ballooning; Antarctica; NASA balloons; Super-pressure balloons; LDB; ULDB

1. Introduction

Numerous conferences and workshops have been held to commemorate the centennial anniversary of the 1912 discovery of cosmic rays on a manned balloon by Victor Hess while conducting an experiment to understand radiation changes with altitude. He received a Nobel prize for that discovery in 1936. The Montgolfier brothers are credited with inventing and experimenting with balloons in France more than 200 years ago. Figs. 1–3 illustrate the evolution in balloon designs over this span of almost two centuries, starting with the Montgolfier invention (Fig. 1). In the early days, balloons were usually coated fabric filled with hydrogen gas (Jones, 2002). Scientists used them to carry instruments aloft to make in situ measurements of, among other things, atmospheric pressure and temperature. Some of those intrepid scientists suffocated or died of exposure in the bitterly cold upper atmosphere.

Large rubberized balloons capable of reaching altitudes of about 20 km in the atmosphere were introduced in the early 1930s (Fig. 2). Aeronauts in sealed, airtight capsules were able to survive to 60,000 feet (~18 km). An altitude record of 72,395 feet set in 1935 stood for 12 years, indicating a limit for rubberized balloons.

In 1950 Otto C. Winzen patented the modern day, natural shape balloon (Fig. 3). Those polyethylene balloons with integral load tapes could carry heavy payloads to around 100,000 feet (~30 km). They played a significant role in paving the way for the U.S. manned space flight program, and they have revolutionized ballooning. Polyethylene balloon film can be extruded into long sheets that can be cut into desired gore patterns. The gores can be heat sealed with load-bearing tapes integrated into the seals, which enables arbitrarily large balloons that can attain very high altitudes. The float altitude depends, of course, on the size of the balloon and the suspended weight. In any case,

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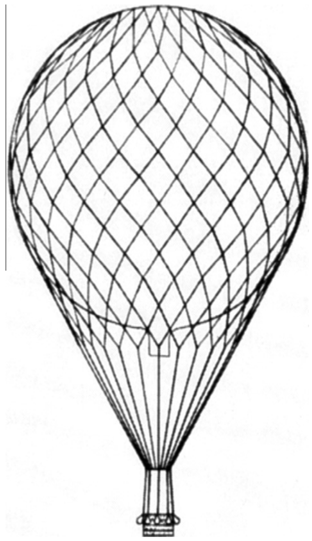

Fig. 1. Illustration of net suspension for varnished silk bag balloon (ca. 1784).

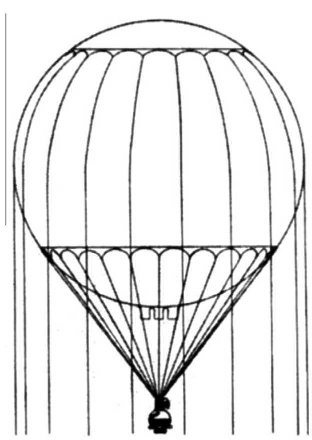

Fig. 2. Illustration of catenary suspension for rubberized fabric balloon (ca.1930).

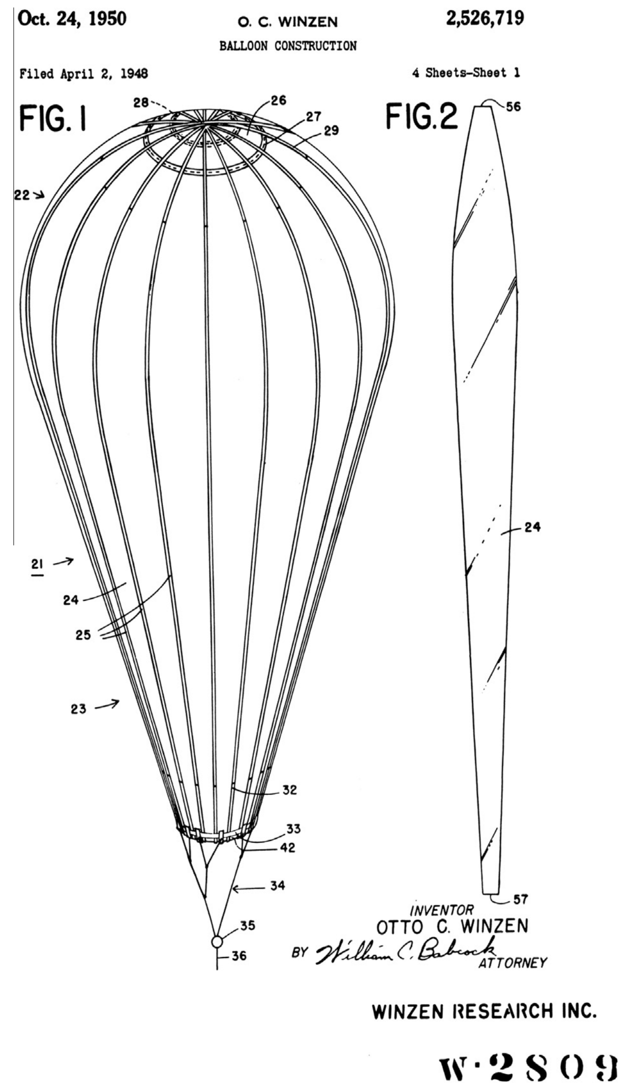

Fig. 3. Copy of Otto C. Winzen's 1950 patent for modern-day, natural-shape balloon.

ballooning has provided a unique capability for frequent access to near-space for a variety of science instruments ranging in mass from a few kilograms to approximately 2000 kg. Furthermore, ballooning has produced a steady stream of new instrumentation and science results for several decades that have raised new questions, which led to numerous additional balloon flights and some new space missions of relatively small satellites. It is generally true that a satellite launch for any discipline reduces its interest in balloon flights, because of the enormous difference in their exposure times.

The vented zero-pressure balloons used today are in equilibrium with the atmosphere. They have changed only incrementally from balloons introduced in the 1950s (Jones, 2005). Since that time, large polyethylene balloons have been employed for a variety of scientific pursuits and technological developments. Approximately 85% of NASA's balloon flights over the past decade have supported investigations of astronomy and astrophysics disciplines needing massive payloads for observations of cosmic rays, X-rays, gamma rays, cosmic microwave background, infrared/sub-mm astronomy, and high-energy neutrinos. About 15% supported non-astronomy and astrophysics disciplines, including Earth science, solar physics, heliospheric physics, and geospace sciences.

2. Antarctic long duration ballooning

Modern scientific balloons are very large polyethylene structures capable of carrying up to 3,600 kg (8,000 lbs.) payloads (suspended weight) into the near space environment above about 99.5% of the Earth's atmosphere. Fig. 4 illustrates the gigantic size of one of these polyethylene balloons, which have carried science, applications, and technology payloads for periods of 1–2 days since the 1950s. Launches have occurred from various locations around the world. Antarctica is the premier launch site,

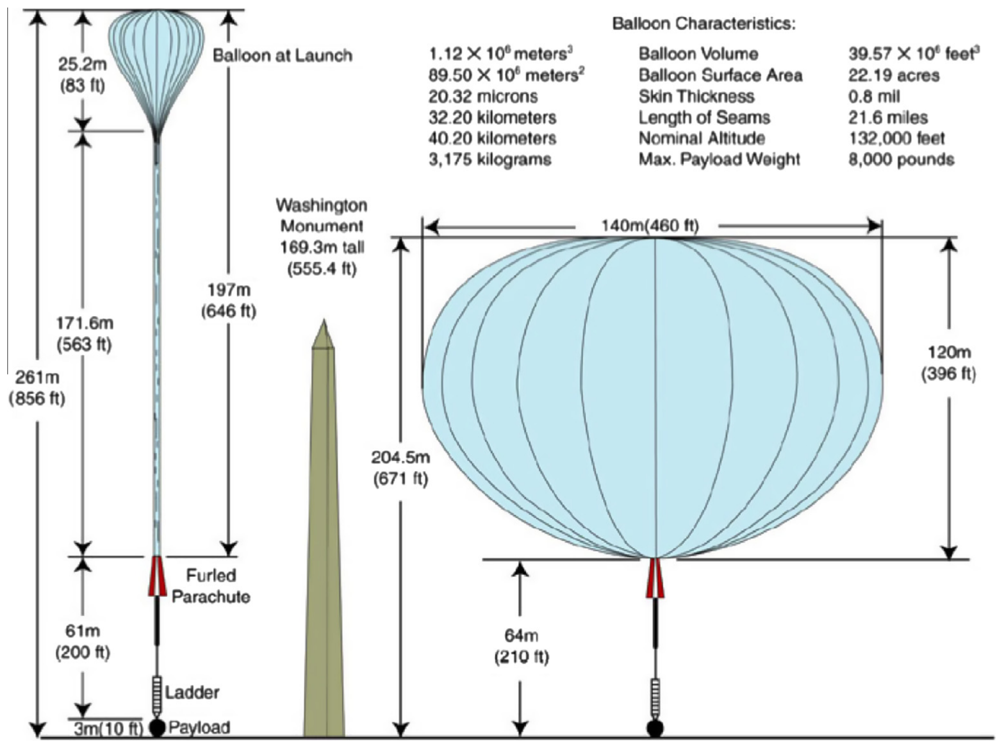

Fig. 4. Illustration of a modern, large, zero-pressure polyethylene balloon.

because circumpolar winds during the Austral Summer facilitate long-duration flights during one to three circumnavigations of the continent in constant sunlight.

In the early 1990s NASA extended balloon flight durations to 10–20 days by conducting launches in the continuous daylight during the Antarctic summer, and taking advantage of the nearly circumpolar stratospheric wind vortex. These so-called LDB (long-duration balloon) flights employ zero-pressure polyethylene balloons identical to those utilized for conventional flights, which are typically limited to 1–2 days by gas loss during day–night transitions. A sea change (broad transformation) in scientific ballooning occurred with the inauguration of LDB flights around Antarctica. Those circumpolar flights have been spectacularly successful, with many investigations utilizing multiple flights of payloads that are recovered, refurbished, and reused to minimize life-cycle costs (Seo, 2012). The attainment of 25–32 day and 35–55 day flights, respectively, in two and three circumnavigations of Antarctica has greatly increased the expectations of scientific users.

Requests for participation in the Antarctic LDB program, a NASA partnership with the U.S. National Science Foundation Office of Polar Programs (NSF/OPP), exceed the current capacity of two–three flights per annual campaign. In 1997, and again in 1998, NASA launched a 13-day flight from Fairbanks, Alaska that flew westward over Russia and onward across the Atlantic to Canada before being terminated and having the payload recovered in western Canada. Realizing that polar flights in the Northern Hemisphere could potentially offer a nearly perfect complement to Antarctic flights, given appropriate international agreements, the Swedish Space Corporation (SSC)/Esrange and NASA inaugurated a joint capability for medium-duration scientific balloon flights from Sweden to Canada in 2005. The long-term goal was to seek international over flight agreements that would allow circumnavigation of the globe in the Northern Hemisphere.

3. Ultra long duration balloon missions

The constant sunlight during local summer in the Polar Regions allows vented, zero-pressure balloons (in equilibrium with the atmosphere) to maintain their float altitudes for long periods of time. However, mid-latitude flights using zero-pressure balloons typically last only a few days, because some of the ballast (which is limited by the balloon's carrying capacity) must be dropped at each day-night transition to maintain float altitude. Constant volume super-pressure balloons capable of carrying heavy payloads to sufficiently high altitudes would undoubtedly bring another sea change in scientific ballooning by enabling long-duration missions at mid-latitudes. Fig. 5 illustrates the expected altitude performance of super-pressure and zero-pressure balloons. The volume of zero-pressure balloons used for conventional and polar LDB flights changes as the ambient atmospheric pressure changes, causing large altitude droop at night. By contrast, a constant volume super-pressure balloon should maintain essentially constant altitude, thereby allowing LDB, including ULDB, flights in non-polar regions. This virtually new capability would facilitate a much broader range of science

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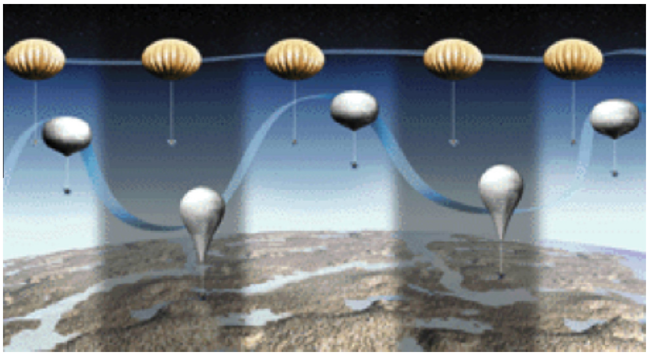

Fig. 5. Altitude stability comparison of super-pressure (top) and zero-pressure (bottom) balloons for day-night excursions.

and technology investigations than are currently possible with balloons.

Long-duration flights offer a proven and cost effective way of carrying heavy payloads to the edge of space. More flights of longer duration are needed to fulfill astrophysics science goals. The test flight of a 7 million cubic feet (MCF) super-pressure balloon (SPB) launched in December 2008 and terminated in February 2009 after 54 days aloft, while on its third circumnavigation of Antarctica, shows the promise of this entirely new balloon. It achieved a new flight duration record, and its performance (altitude and differential pressure) remained steady with no gas loss. It was terminated only because its flight path was tending to go off the continent: otherwise it could have flown considerably longer. Fig. 6 compares the altitude stability of this SPB with those of two LDB payloads flown during the same season. As expected, the SPB maintained a stable altitude with little variation, whereas the zero-pressure LDB balloons drooped significantly during a diurnal cycle.

This new capability will enable important and cost effective observations in a variety of scientific disciplines. Fig. 7 illustrates the pumpkin shape of NASA's SPB design, which is the first entirely new balloon since Otto Winzen's natural shape balloon in 1950. The second SPB test flight in Antarctica, a 0.42 million cubic meters (MCM) balloon

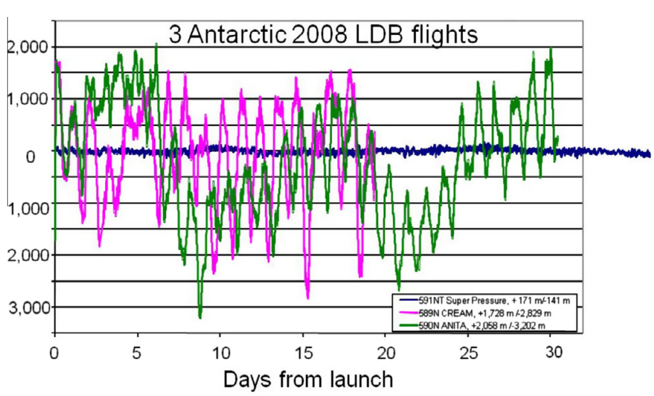

Fig. 6. Comparison of altitude variations in meters for first 30 days of 7 MCF SPB test flight of 54 days with two Antarctic LDB flights (CREAM 19 days; ANITA 30 days) during the same 2008/2009 season.

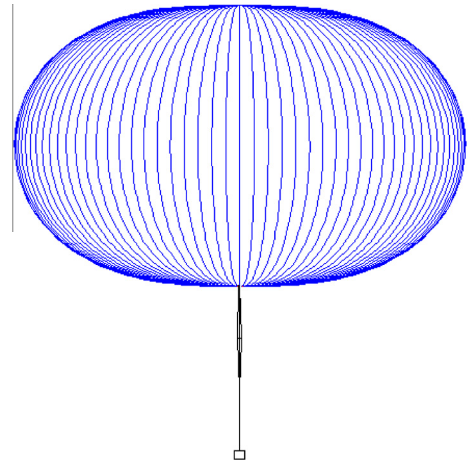

Fig. 7. Illustration of NASA's pumpkin-shape super-pressure balloon design, the first new balloon since 1950.

launched on January 9, 2011, flew for 22 days. Although it had a shorter duration, it's flight performance matched predictions very closely. It carried a suspended payload of 1,815 kg, and it fully deployed just before reaching the target float altitude at essentially no differential pressure.

The frequent access to space provided by small space missions (e.g., Small Explorers – SMEX) has accelerated scientific and technical innovation in the space sciences. Balloon-borne payloads provide similar benefits at still lower cost, and a new generation of ULDB missions with 100 days or more of observing time near the top of the atmosphere appears imminent. Currently, ULDB is defined as a 1000 kg science instrument suspended along with its flight support equipment from a SPB floating above 33 km for about 100 days. Comparable flights of smaller instruments to higher altitudes around 38 km on larger SPB's are also being pursued.

4. Balloon borne astrophysics research

Antarctic LDB flights have supported various disciplines over the past two decades with important results. Perhaps the best known example is the Boomerang detailed map of Cosmic Microwave Background (CMB) temperature fluctuations showing the Euclidian geometry of the universe that led to the 2006 Balzan Prize for Astronomy and Physics (Balzan Prize, 2006). More recent results include the unexpected surplus of high-energy cosmic ray electrons observed by the Advanced Thin Ionization Calorimeter (ATIC). This often cited result is sometimes attributed to an indirect detection of dark matter, but the surplus could instead come from a previously unidentified and relatively nearby cosmic object within about 1 kilo parsec of the Sun (Chang et al., 2008). The Balloon Experiment with a Superconducting Spectrometer (BESS) has conducted a negative search for annihilation signatures of dark matter in the antiproton channel (Abe et al., 2012). The electron excess in ATIC and lack of excess antiprotons in BESS provide interesting constraints on dark matter models.

A high level overview of just a few key on-going balloon-borne investigations of cosmic rays is given below. This limited scope precludes many high priority, non-cosmic-ray balloon-borne investigations, and some cosmic-ray balloon investigations are not addressed because they are expected to be presented independently.

4.1. Cosmic ray energetics and mass (CREAM)

Traditional cosmic ray origin and propagation models are constrained by spectral hardening below the "knee" reported by CREAM, which has accumulated 161 days of exposure in six flights around Antarctica, including its record-breaking first flight of 42-days in 2004–05 (Seo, 2012). This is believed to be the longest duration ever achieved by a single balloon-borne project: it is equivalent to the original design goal for two nominal ULDB flights. The instrument (shown in Fig. 8) meets the challenging and conflicting requirements of a large enough geometry factor to collect adequate statistics for the low flux of high-energy particles, and yet stay within the 1000 kg mass limit for ULDB flights. The CREAM instrument is a quarter-scale version of the Advanced Cosmic-ray Composition Experiment for the Space Station (ACCESS) given high priority by the National Research Council to investigate the signature of rigidity dependent particle acceleration in supernova (Decadal Study, 2001). This signature leads to a characteristic change in elemental composition between the limiting energies for protons and iron, respectively about $\sim 10^{14}$ and $\sim 26 \times 10^{14}$ eV. This change is believed to be associated with a limit to supernova acceleration and the "knee" feature around 10^{15} eV seen in air shower data for the all-particle spectrum.

Fig. 8. Photograph of CREAM instrument during its first hang test at NASA Wallops Flight Facility in 2004: from E. Seo, Principal Investigator.

The CREAM goal was to extend direct measurements of cosmic-ray composition to the highest energies practical with LDB and ULDB flights in Antarctica (Ahn et al., 2010). It's charge identification and energy measurement systems are capable of precise measurements of elemental spectra for $Z = 1$–26 nuclei over the energy range $\sim 10^{11}$–10^{15} eV. It uses double layers of finely segmented Silicon detectors, scintillator based timing detectors, and an imaging Cherenkov camera for charge measurements. Like ACCESS, it combines a calorimeter capable of measuring $Z = 1$–28 particles and a Transition Radiation Detector (TRD) capable of measuring $Z = 3$–28 particles to span the broadest possible range of atomic numbers and energies (Ahn et al., 2007). Only the calorimeter is capable of measuring the most abundant H and He at the highest energies, but its area must be limited to stay within an acceptable mass. The relatively low mass TRD can have a large collecting area, enabling it to see adequate numbers of elements heavier than helium. A substantial fraction of the cosmic rays can be measured in both detectors, thereby providing a direct inter-calibration for $Z \geqslant 3$ particles.

The CREAM science objectives require spectral measurements of H and He for energies 10^{12}–10^{15} eV energies, with exposure great enough to measure C, O, and Fe to 10^{15} eV per nucleus. It has reported unprecedented measurements of individual cosmic-ray nuclei spectra from hydrogen through iron over more than two decades in energy leading up to the "knee" in the all-particle spectrum. One of its payloads (dubbed ISS-CREAM) is now being reconfigured to fly on the International Space Station (ISS) to increase its statistics by approximately an order of magnitude during a one-year minimum, three-year goal mission (Seo et al., 2013).

4.2. Super-trans iron galactic element recorder (Super-TIGER)

Super-TIGER builds on the success of its Trans-Iron Galactic Element Recorder (TIGER) predecessor, the first LDB mission to complete two circumnavigations of Antarctica. Two years after that achievement in 2001, TIGER completed 1.5 rounds of Antarctica in 2003. Those two flights yielded a total of 50 days of data, and they produced the first well-resolved elemental abundance measurements of the Ga, Ge, and Se elements (Rauch et al., 2009). The interpretation of the TIGER data was limited, however, by the small number of events detected. The much larger Super-TIGER utilizes the same detectors and techniques as TIGER: plastic scintillator dE/dx detectors, Cherenkov counters with two different refractive indices, and scintillating fiber hodoscopes. It is estimated that with 60 days at float Super-TIGER would obtain approximately an order of magnitude increase over TIGER in the number of events detected.

The Super-TIGER team recently completed an exceptionally successful Antarctic LDB flight to investigate the origins of cosmic rays. The instrument was launched from

McMurdo Station, Antarctica, December 8, 2012, and its flight was terminated February 1, 2013, due to concerns about increasing instability in the jet stream over Antarctica. In nearly three circumnavigations of the Continent (Fig. 9) the payload flew for 55 days, 1 h, and 34 min at altitudes ranging from about 120,000 feet to 130,000 feet. The flight set two duration records: (1) longest flight for a heavy scientific payload and (2) longest flight of a heavy-lift scientific balloon, including NASA's super pressure balloons. Its measurements are expected to provide definitive tests of current theories about the origin and acceleration sites of cosmic ray nuclei and the mechanism by which different nuclei are selected for acceleration.

The first Super-TIGER flight undoubtedly measured the abundances of $30 \leqslant Z \leqslant 42$ elements with unprecedented individual element resolution. Those data can test the emerging model of cosmic-ray origin in massive (i.e., OB) star associations, in addition to models for atomic processes by which nuclei are selected for acceleration to cosmic ray energies. This model is supported by the observed ^{22}Ne/^{20}Ne and ^{58}Fe/^{56}Fe overabundances in cosmic rays measured by the Cosmic Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer (ACE) spacecraft (Binns et al., 2005). It is also supported by the source abundance ordering of refractory and volatile elements in cosmic rays measured by TIGER (Rauch et al., 2009). The collective data indicate a cosmic-ray source with approximately 80% of the mass having a composition characteristic of the material of our Solar System, and 20% having a composition characteristic of outflow from massive stars in OB associations.

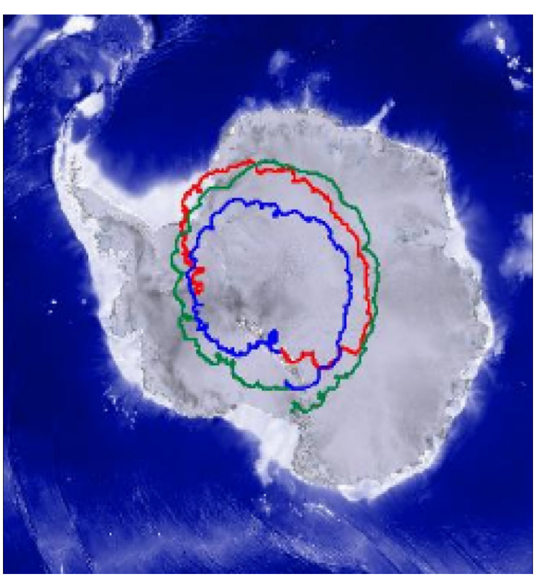

Fig. 9. Trajectory of 55-day Super-TIGER flight around Antarctica during the 2012/2013 austral season. First, second, and third circumnavigations are shown, respectively, in green, blue, and red colors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.3. Antarctic impulsive transient antenna (ANITA)

The balloon-borne ANITA was designed to test the fundamental laws of high-energy physics and astrophysics by examining the distant universe in the "light" of neutrinos, the most penetrating particles yet discovered in the universe (Gorham et al., 2010). Neutrino emission is an inevitable consequence of the decay of pions produced by colliding matter in the accretion disks surrounding Massive Black Holes (MBH), almost certain to be the engines for Active Galactic Nuclei (AGN). These black holes are expected to produce neutrinos with 10^14–19 eV energies. Neutrinos are able to escape directly from close to the event horizons of massive black holes or from the early moments of gamma-ray burst events, both of which are believed to be strong neutrino sources. Constraints on neutrino fluxes from such sources will also constrain their role in the origin of $> 10^{19}$ eV cosmic rays. Particles at such high energies must originate in the most extreme astrophysical environments, although there is no accepted theory for their production.

Neutrinos from interactions of the highest energy particles with the cosmic microwave background probe the most extreme cosmic environments and their source evolution history. The low flux and low interaction probability of the highest-energy ($>10^{18}$ eV) neutrinos require enormous detector volumes. ANITA'S experimental concept makes use of the very large target volume (several million km^3) of extremely radio transparent ice (attenuation lengths > 1 km) to look deep into the ice sheet for neutrino interactions. See Fig. 10 for an illustration of the measurement concept. Strong radio impulses are produced by coherent radio Cherenkov emission from the charge asymmetry in the particle cascades associated with the interactions: the so-called Askaryan effect. Neutrinos above $\sim 10^{18}$ eV interacting anywhere within ∼700 km of the

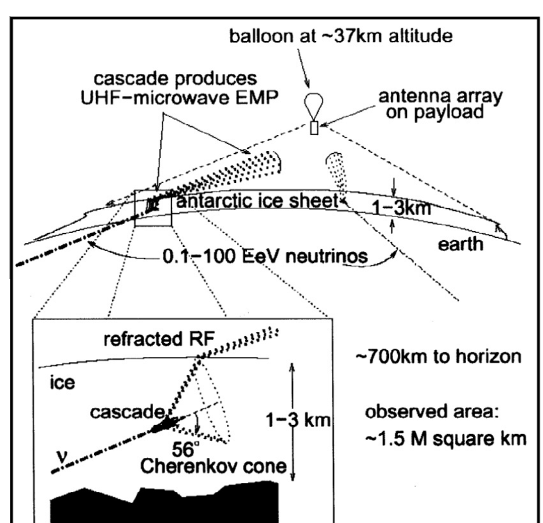

Fig. 10. Schematic of ANITA balloon-borne measurement concept: from P. Gorham, Principal Investigator.

balloon-borne ANITA payload can be detected. The neutrino signature would reflect the spatial and angular distribution of ultra-high-energy cosmic rays arising from exotic processes, such as acceleration in γ-ray bursts, more conventional dynamo acceleration near AGN black holes, or the top-down decay of early universe relics.

The ANITA instrument completed its first science flight with 35 days aloft in January 2007 and its second flight of 30 days in January 2009. Its third flight is planned for launch in December 2014. Although this unique balloon-borne experiment was designed to detect radio signals from cosmogenic neutrinos (Beresinsky and Zatsepin, 1969), it has turned out to be sensitive also to the highest energy air showers. The ANITA payload is among the largest ever flown in the balloon program, over 25 ft (8 m) high and about 18 ft (6 m) wide at the base. The flight weight, including the NASA-supplied supporting hardware, is about 2 metric tons, and power requirements are about 550 Watts. This low-power achievement is one of the enabling technologies for ANITA, since commercially available data digitizers running at such high speeds would likely require several kilowatts of power. The radio impulses measured by the entire antenna array are stored in onboard solid-state drives that are recovered with the payload following flight termination. Subsequent analysis reconstructs the direction of each impulse using techniques of radio-pulse-phase interferometry, yielding good angular resolution of about ~15 arcmin in elevation and ~50 arcmin in azimuth.

5. Enabling new balloons and space missions

The NASA Balloon Program provides unique opportunities for high-priority science and instrument development, including training of students, engineers, and principal investigators for future balloon and/or space missions. This contribution has been diminished by the declining flight rate in recent years due to a shortage of funding. Additional support is needed for both payloads and enhanced capabilities so ballooning can resume its central role in the future of space science. High priority needs include continuation of the three-launch capability in Antarctica to increase the science now being obtained, and a dedicated aircraft to ensure timely (same season) payload recovery and lower refurbishment costs of the instruments. A complementary capability of three or more Arctic flights each year during the Northern Hemisphere summer is also needed.

The NASA Balloon Program is nearing completion of its delayed development and demonstration of super-pressure balloons to enable an operational capability of long-duration mid-latitude flights. It will need to extend that capability to lift 1000-kg instruments to higher altitudes, along with modest trajectory control to enable ULDB flights of about a hundred days. The 2010 Astrophysics Decadal Study, commonly called Astro2010, strongly supported this new capability for studies of cosmic microwave background radiation and particle astrophysics on an accelerated development timeline not available for larger orbital missions: see Decadal Study (2010) reference.

6. Particle astrophysics experiments on the ISS

Particle astrophysics research can address many of the objectives in the National Science and Technical Council list of greatest unanswered questions of Physics: e.g., What is Dark Matter? How do Cosmic Accelerators Work and What are they Accelerating? See Interagency Working Group (2004) reference for complete list. A large fraction of them are addressed in NASA's Strategic Goals developed from decadal surveys with community input (NASA Strategic Plan, 2006; NASA Science Plan, 2007). The investigations AMS (Aguilar et al., 2013), CALET (Torii, 2013), CREAM (Seo et al., 2013), and JEM-EUSO (Takahashi, 2009) each address one or more of these unanswered questions, and all four are well suited for the International Space Station (ISS). Assuming that they will fly on the ISS nearly simultaneously, their collective instrument capabilities and science objectives constitute a virtual cosmic ray observatory spanning a very large part of the cosmic ray spectrum. Fig. 11 illustrates the locations (or intended locations) of these four Particle Astrophysics instruments on the ISS.

They will search for signatures of dark matter annihilation by measuring electron spectra with reliable statistics and high resolution, and search for distinct features in high-energy spectra as evidence of powerful nearby (<1 kpc) particle accelerators. They will determine the effects of particle propagation in the interstellar medium by measuring primary and secondary nuclei spectra while extending hydrogen to iron elemental spectra to beyond 10^{15} eV to understand their origin and source processes and to study the nature of the "knee" in the all-particle spectrum. One would survey the ultrahigh energy

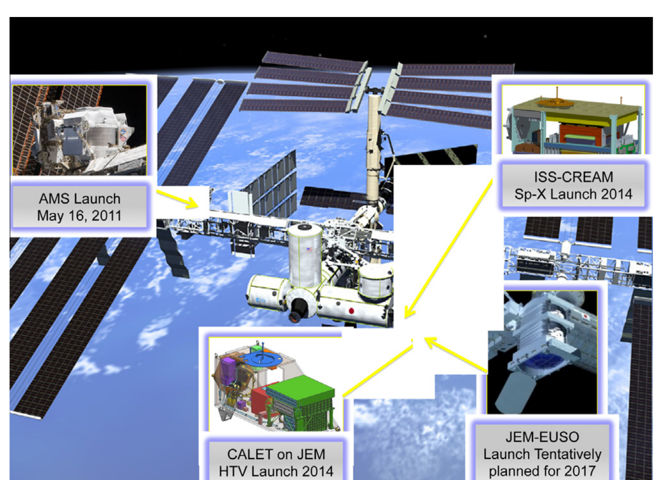

Fig. 11. Illustration of virtual ISS cosmic ray observatory comprised of the AMS, CALET, CREAM, and JEM-EUSO instruments.

($>10^{19}$ eV) particle sky and measure particle arrival directions to locate sources within 50 Mpc, discover their nature, and test our understanding of fundamental physics in the universe far beyond Large Hadron Collider (LHC) energies: it would also search for ultrahigh energy neutrinos (Takahashi, 2009). The science objectives of these missions validate the importance of the ISS for enabling a wide range of investigations crucial for understanding our universe and its fundamental nature.

6.1. Alpha magnetic spectrometer (AMS)

The AMS instrument was launched by Space Shuttle Endeavor and installed on the ISS in May 2011 to conduct a multi-messenger study of cosmic rays, including solar energetic particles and searches for antimatter and dark matter in cosmic rays (Aguilar et al., 2013). The precise AMS measurements utilizing technology developed in particle physics and modified for space application will provide the means to confirm or refute much of the prior data (e.g., Adriani et al., 2009; Abdo et al., 2009). Particles are distinguished from antimatter by observing the oppositely curved tracks of particles with positive and negative charges traversing the strong magnetic field.

6.2. CALorimetric electron telescope (CALET)

The CALET mission was conceived to extend high-energy electron observations to high energies beyond existing data (Chang et al., 2008; Adriani et al., 2009; Abdo et al., 2009). Central to the design is a deep calorimeter (~30 radiation lengths) to provide excellent energy resolution and high background rejection, thereby enabling CALET to study high-energy electrons. The Japanese led CALET was proposed as an international project for ISS utilization. It will be launched on the Japanese Space Exploration Agency (JAXA) H-rocket Transfer Vehicle (HTV) and placed on the Japanese Experiment Module (JEM) Exposed Facility (EF) for its planned five year mission lifetime (Torii for the CALET Collaboration 2013). Japan invited teams from the US (CALET-US) and Italy (CALET-IT) to join the international program. JAXA requested the CALET team to study a reduced size ~500 kg instrument that could be approved for launch on the HTV within the up-mass budget available to Japan. The smaller configuration maintains the high quality of individual measurements, but with an integrated exposure reduced by a factor of ~3 compared to the original instrument. This limits the number of gamma ray sources that CALET can investigate at high energy, but it maintains the important objectives for high-energy electrons and nuclei. A scientific peer review panel assembled by JAXA assessed the viability of the reduced size and found that CALET remains an exciting scientific mission, and it recommended that it proceed with a five-year lifetime. The final hurdle was passed when the U.S. and other international partners agreed to extend the lifetime of the ISS to 2020, thereby enabling a five-year mission.

6.3. Cosmic ray energetics and mass for the ISS (ISS-CREAM)

The balloon borne CREAM project to search for features in cosmic ray elemental spectra was discussed above in Section 4.1. One of its instruments has been reconfigured to fly on the ISS, in order to increase the statistics by an order of magnitude during its one-year minimum, three-year goal mission (Seo et al., 2013). The Principal Investigator's home institution, the University of Maryland (UMD), is responsible for the instrument development in cooperation with several institutions in the U.S., South Korea, France, and Mexico. The NASA Goddard Space Flight Center (GSFC) Wallops Flight Facility provides project management and engineering support, system-level integration, and the payload environmental test program. The ISS Program Office at Johnson Space Center (JSC) provides Flight and Ground Safety process support, and serves as the point of contact for Launch Vehicle Integration Engineering. The Astrophysics Division of the NASA Science Mission Directorate, which sponsored balloon-borne CREAM, also sponsors the ISS-CREAM payload for flight on NASA's share of the JEM-EF. The payload will be integrated at Kennedy Space Center (KSC) and launched onboard a Space-X launch vehicle carrying ISS resupply cargo.

6.4. Extreme universe space observatory on the JEM-EF (JEM-EUSO)

The JEM-EUSO mission is being studied by a 13-country international collaboration led by JAXA and RIKEN (Institute of Physical and Chemical Research of Japan) for launch after 2017. Attached to the JEM-EF on schedule, JEM-EUSO would be the first spaced-based observatory to use the Earth's atmosphere as a gigantic detector of a large number of extreme energy, $>6 \times 10$^19 eV, cosmic rays (Takahashi, 2009). Its goal is to open a new field of astronomy through the charged particle channel and, thereby, enlarge the energy reach of fundamental physics probes to the most powerful accelerators in the universe. The U.S. participants are currently studying the key Global Light System (GLS), a ground-based worldwide network of remotely operated light sources (lasers and Xe flashers) for JEM-EUSO calibration and monitoring (Santangelo et al., 2013). The GLS will be supplemented with an aircraft system. Calibrated UV lasers and Xenon flash lamps are capable of generating optical signatures with characteristics similar to extensive air showers initiated by cosmic rays within the JEM-EUSO field of view. The JEM-EUSO mission should be able to reconstruct the pointing directions and energies of the lasers and flash lamps, in order to monitor the detector's triggers, and accuracy of energy and direction reconstruction. A prototype of the

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instrument is planned to fly on a balloon starting in 2014 to test its design. Prototypes of the GLS would be used to test and calibrate the balloon-borne prototype, dubbed EUSO-Balloon, during its flights (Von Ballmoos et al., 2013). These contributions allow the US team to participate in all aspects of JEM-EUSO science. They also allow the NASA ISS Program to contribute the attachment point resources and up mass (payload the vehicle is capable of carrying from the ground into orbit) needed to accommodate the mission on the ISS.

7. Concluding remarks

Scientific ballooning supports cutting-edge science discoveries with state-of-the-art instruments in a rapid turnaround environment. The importance of ballooning to achievement of NASA's objectives was recognized in the early days of the space program, and it has since been emphasized in several strategic roadmaps. Driven by science and technology development, balloon investigations play important roles in training of experimental space scientists and engineers, in addition to development of new instruments for space flight. The Antarctic LDB program, which provides flight durations for as much as 55 days, has been spectacularly successful. The completion of superpressure balloon development will undoubtedly enable LDB flights at mid-latitudes and, hopefully, even more spectacular ULDB flights.

The ISS is even more attractive than ULDB flights for investigations that study the low fluxes of high-energy cosmic rays. Cosmic-Ray/Particle Astrophysics investigations are solicited as a program element in the Astronomy and Physics Research and Analysis (APRA) program of NASA's annual Research Opportunity in Space and Earth Science (ROSES) solicitation [http://nspires.nasaprs.com]. This program element has traditionally supported investigations utilizing payloads flown on large stratospheric balloons or similar-class payloads flown as flights of opportunity on space missions. In recent years it has also supported suborbital class investigations that utilize the ISS. An amendment to 2010 ROSES specifically solicited ISS investigations in competition with traditional suborbital investigations. Stand Alone Mission Of Opportunity Notices (SALMON) from NASA also solicit small complete missions requiring flight on high-altitude scientific balloon platforms, the ISS, or as secondary/hosted payloads on larger missions.

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Appendix A. List of acronyms

ACCESS	Advanced Cosmic-ray Composition Experiment for the Space Station
ACE	Advanced Composition Explorer
AGN	Active Galactic Nuclei
AMS	Alpha Magnetic Spectrometer
ANITA	Antarctic Impulsive Transient Antenna
APRA	Astronomy and Physics Research and Analysis
ATIC	Advanced Thin Ionization Calorimeter
BESS	Balloon Experiment with a Superconducting Spectrometer
CALET	CALorimetric Electron Telescope
CMB	Cosmic Microwave Background
CREAM	Cosmic Ray Energetics And Mass
CRIS	Cosmic Ray Isotope Spectrometer
EF	Exposed Facility
GLS	Global Light System
GSFC	Goddard Space Flight Center
HTV	H-rocket Transfer Vehicle
ISS	International Space Station
ISS-CREAM	Cosmic Ray Energetics And Mass for the ISS
JAXA	Japanese Space Exploration Agency
JEM	Japanese Experiment Module
JEM-EUSO	Extreme Universe Space Observatory on the JEM-EF
JSC	Johnson Space Center
KSC	Kennedy Space Center
LDB	Long-duration Balloon
LHC	Large Hadron Collider
MBH	Massive Black Holes
MCF	million cubic feet
MCM	million cubic meters
NASA	National Aeronautics and Space Administration
NSF/OPP	National Science Foundation Office of Polar Programs
RIKEN	Institute of Physical and Chemical Research of Japan
ROSES	Research Opportunity in Space and Earth Science
SMEX	Small Explorers
SPB	Super-pressure Balloon
SSC	Swedish Space Corporation

Super-TIGER	Super-Trans Iron Galactic Element Recorder
TIGER	Trans-Iron Galactic Element Recorder
TRD	Transition Radiation Detector
ULDB	Ultra-long-duration Balloon
UMD	University of Maryland

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