Particle Astrophysics in NASA’s Long Duration Balloon Program

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Abstract

A century after Victor Hess’ discovery of cosmic rays, balloon flights still play a central role in the investigation of cosmic rays over nearly their entire spectrum. We report on the current status of NASA balloon program for particle astrophysics, with particular emphasis on the very successful Antarctic long-duration balloon program, and new developments in the progress toward ultra-long duration balloons.

Keywords: particle astrophysics, scientific ballooning, cosmic rays

1. Introduction

It is remarkable in this current generation of highly developed spacecraft exploration of the solar system that scientific ballooning still remains a powerful and effective method of particle astrophysics investigation. More than a century after balloon flights were first used [1] to establish the extraterrestrial nature of cosmic rays, balloon-based investigations still play a crucial role in their elucidation. Since the time of Viktor Hess’ initial studies, a myriad of new techniques for the study of high energy radiation from the cosmos has been developed, including sophisticated methods utilizing direct detection, Cherenkov, and fluorescence radiation, observed on the ground; and particle detection in a wide range of spacecraft. However, the unique role of cosmic ray investigations from balloons has not yet been superseded, for a variety of reasons: from the relatively low cost and risk for development of new and novel instruments as balloon payloads, the large lift capacity of a balloon system for modest costs, and in some cases, due to the fact that the suborbital trajectory of the balloon system is a necessary part of the science requirements.

The term particle astrophysics was initially synonymous with cosmic ray studies, but within the last several decades it has become increasingly evident that still-undiscovered fundamental particles may play a dominant role in the composition of the non-baryonic dark matter, which makes up of order a quarter of the closure density of the universe. Thus the scope of particle astrophysics has expanded to include dark matter investigations, although we cannot yet be certain that the dark matter will yield to a particle physics solution.

In addition to the study of charged particles, high energy gamma-rays, and possible neutrons of extra-solar origin, neutrinos have now also emerged as another member of the particle astrophysics panoply. The fluxes of high energy neutrinos in the TeV to EeV range are closely coupled to cosmic acceleration processes, and may provide “smoking-gun” evidence for the sources of both galactic and extragalactic cosmic rays. For the latter, cosmogenic EeV neutrinos are direct byproducts of intergalactic scattering of the highest energy cosmic rays, and have the potential to probe cosmic ray accelerators even back to the earliest epochs of cosmic ray sources.

Balloon-borne payloads are active contributors to all of these particle astrophysics topics. In the following report, we provide a “user’s view” of the current state-of-the-art of NASA ballooning and highlight a number of the current and planned missions. While this will not be a complete review of the NASA particle astrophysics program, we hope it will provide a useful introduction to an exciting and accessible part of the NASA astrophysics program, one that is often overshadowed...
by spacecraft missions, but has produced a very compelling portfolio of scientific accomplishments in the last few decades.

2. Overview of balloons & capability

Before turning to the payloads themselves, we first summarize the payload and flight profile capabilities of the program.

Fig. 1 shows a graphical summary of the scale of a typical balloon in various stages of the launch and ascent to float. Helium initially inflates only a relatively small volume of the balloon at ground level, and the flight train is typically around 800 ft long at liftoff. Balloon launches and flights produce very low dynamics compared to a rocket launch, and thus payloads may dispense with the rigorous vibration qualification required of spacecraft payloads. The only significant dynamic event is at termination after the flight is complete, and the parachute opens after several tens of km free fall from the float altitude (typically 120Kft) down to about 80Kft, where the atmosphere has enough density to fill the parachute. By this time the payload is falling at a high velocity, and the jerk from the filling chute can produce several gees of acceleration. Recent modifications to the flight train using dynamic load absorbers have greatly reduced even these dynamics, but payloads are still required to be designed for a maximum 10 gee acceleration at this stage. However, the requirement is only that the payload does not separate from the flight train, and this takes place after the science mission is complete. Thus the science instrument does not have to be designed to operate after this acceleration event, only to survive it in a safe-mode state.

In Fig. 2 we show current altitude vs. lift capabilities for NASA qualified balloons. These come in both zero-pressure balloons (ZPB), and recently now in super-pressure (SPB) versions. ZPBs are vented and stay at equilibrium density/pressure with the surrounding gas at float. Diurnal variations of solar heating and nighttime cooling lead to substantial changes in the internal pressure of the gas, and the equilibrium conditions thus cause a diurnal change in altitude and balloon envelope shape for a ZPB. SPBs were developed to address this drawback in ZPB float profiles, as we discuss below.

The largest ZPBs now routinely carry 2000 kg or more of science weights to altitudes over 130,000 ft (nearly 40km), where the atmospheric overburden is...
Balloon capabilities

Figure 2: Graphical summary of lift capacity for NASA qualified balloons. Here the units MCF is the balloon volume in millions of cubic feet (there are about 35.3 cubic ft per m$^3$).

below 3 mbar, or less than 0.3% of sea level pressure. Flights in Antarctica have now exceeded 55 days at float, and 1-month-at-float has become a more routine expectation as NASA and the National Science Foundation, which manages the Antarctic program, have developed more effective protocols for log-duration flight support.

While costs for such missions have grown steadily as more complex instruments are developed and required for more challenging science, typical missions are still at least an order of magnitude and often two orders of magnitude smaller than equivalent costs to get a comparable payload to low-earth orbit. Thus it has become common to use balloon payloads to validate instruments prior to their promotion as a potential spacecraft instrument, and this has the added benefit of introducing new investigators to the NASA flight hardware development process under a much lower risk and lower cost environment.

2.1. Superpressure balloons.

In contrast to ZPBs, SPBs are not vented, and are designed to maintain a slight overpressure (typically less than 100 Pa – compare this to sea-level atmospheric pressure of $10^5$ Pa) relative to the ambient atmosphere at float. This leads to a vast improvement in their float altitude profile, and almost completely suppresses the diurnal altitude changes. This is illustrated by Fig. 3 which shows the altitude profiles for three payloads that were aloft at the same time during the 2009 austral summer season in Antarctica: ANITA, CREAM, and a 7Mcf SPB test flight, which flew for 54 days during that year.
While ANITA and CREAM saw diurnal variations of 8-10Kft over the 1.8 day period shown here, the variations for the SPB were in the tens of m RMS range.

Super-pressure balloons are still largely in a development phase within the NASA balloon program, although they are now considered part of the proposable launch vehicle inventory, up to the 18 MCF size, although this latter balloon is still in its final testing phases prior to being available for production. The current schedule for the SPB program is shown in Fig. 4 including the proof-flights for the 7MCF and 14MCF balloons, both of which are capable of carrying quite substantial payloads, a thousand kg or more to at least 110Kft.

One of the most important roles that SPBs will play in the future of the balloon program is that they will create the possibility of mid-latitude flights for up to 100 days, engendering payloads that wish to make nightside observations in these regions without paying the stiff penalty of a loss of altitude during the night-time cooling period. To facilitate such flights, southern hemisphere launch sites must be identified which will allow for a complete orbit around the Earth, with overflight agreements from the nations in the flight path. Currently the best potential site appears to be in Argentina, but as yet no agreements have been reached regarding the overflight requirements.

3. Antarctic flights.

Lacking a mid-latitude launch sight and corresponding overflight plan, Antarctica remains the centerpiece of scientific ballooning, affording the longest possible flights. These are made during the austral summer months, early December through early February, when the Polar Vortex creates stable circumpolar flight paths. Payloads can thus also be assured of continuous solar illumination, allowing them to derive all of their operational power from photovoltaics. The drawback is of course that no night flights are yet possible; launch operations during austral winter are not yet under consideration, and in any case circumpolar orbits would not be possible since the stratospheric wind patterns are completely different than the summer months.

The very long possible exposures at float have created a demand for these flight opportunities, and NASA and NSF have responded by expanding the program recently to allow for up to three large payloads to be launched in each of the Antarctic seasons. Fig. 5 shows the results from the most recent season, where three payloads, Super-Trans-Iron Galactic Element Recorder (Super-TIGER), Balloon-borne Large-Aperture Submillimeter Telescope (BLAST-Pol), and E and B Experiment (EBEX, a cosmic background telescope) all completed successful missions, with Super-TIGER breaking the record for the longest flight to date, 55 days over three orbits of the pole. This latter flight illustrates nicely the behavior of the south Polar vortex, which is characterized by stable stratospheric circulation.

Launches are made from near McMurdo Station, at Williams Field, about 10 miles from McMurdo on the Ross ice shelf, which is about 50 meters thick at the launch site, floating over the Ross sea. The shelf is gradually moving toward Ross island, at a rate such that the base has been moved twice already over the last three
decades since the program began. Despite this additional challenge, the smooth, flat surface of the ice shelf provides ideal platform for balloon launches, and the NASA program has become highly adapted to this location, with two large payload integration buildings, and a host of other supporting facilities, and (as many have noted) and a galley with some of the best food in Antarctica!

Since the advent of Antarctic long-duration ballooning in the early 1990’s, there have been several notable scientific results that bear repeating:

- Boomerang flew in the early 1990’s, creating one of the first detailed maps of Cosmic Microwave Background (CMB) temperature fluctuations, and demonstrating the Euclidean geometry of the universe. This led to the 2006 Balzan Prize for Astronomy and Physics [2], and was instrumental in engendering follow-on space missions such as the Cosmic Background Explorer (COBE) and its successors WMAP and Planck.

- In a 2007 flight the Advanced Thin Ionization Calorimeter (ATIC) measured an unexpected excess of 300 GeV cosmic ray electrons [3]. These observations, combined with positron evidence from the PAMELA spacecraft, led to speculation that a dark matter particle annihilation signature might be the origin of the anomaly, although current belief now favors a relatively nearby unidentified object such as a pulsar, as the source.

- The 2006-2007 flight of the Trans-Iron Galactic Element Recorder (TIGER) was used to make precise measurements of the abundances of elements from 26Fe to 34Se, leading to some of the best evidence that acceleration of galactic cosmic rays takes place in OB star associations [5]. The record-setting 2012-2013 Super-TIGER flight should provide much higher precision measurements of refractory element abundances.

- The Balloon Experiment with a Superconducting Spectrometer (BESS), a joint Japanese-American
collaboration, flew nine times since 1993, and has made measurements of low-energy antiprotons and searches for anti-helium at levels of precision that lead to useful constraints on certain dark matter models, especially in combination with other experiments such as ATIC and the space-based platforms [4].

- The Cosmic Ray Energetics and Mass (CREAM) experiment has reported a hardening of the cosmic ray energy spectrum below the knee, and this feature appears to be in tension with standard models of propagation for galactic cosmic rays [6]. This result was enabled largely by the six total flights that CREAM was able to achieve in the program, leading to about 160 days of exposure livetime, the largest of any balloon-borne experiment to date.

- The Antarctic Impulsive Transient Antenna (ANITA) mission was flown initially in 2006-2007 as the first NASA ultra-high energy neutrino payload. In the process of calibrating the payload at the Stanford Linear Accelerator Center (SLAC), ANITA made the first measurements of the Askaryan effect – radio Cherenkov emission from the negative charge excess in an electromagnetic cascade – in ice, using a 7.5 ton block-ice target in the SLAC End Station A experiment hall. This experiment was chosen for the cover of Physical Review Letters, the premier fundamental physics journal worldwide, as seen in Fig. 6.

- Then, during the first ANITA flight, the payload not only set the best world limits on UHE neutrino fluxes [7, 8], but made a serendipitous observation of radio emission from 16 ultra-high energy cosmic rays, which interacted in the Antarctic atmosphere, producing a narrow radio beam which then reflected off the ice surface up to the payload. This unexpected discovery was not the first time radio pulses were seen from cosmic rays, but it was the highest energy set of such events ever recorded, and was unique in that the instrument was completely self-triggered. These led to a second Physical Review Letters cover, shown in Fig. 7 [9].

4. Future Particle astrophysics payloads.

As noted above the current very long near-space exposures possible for payloads in the Antarctic long-duration balloon program has led to renewed interest in these opportunities, and several new particle astrophysics efforts will be highlighted here.

![Figure 7: PRL cover for ANITA-1 discovery of UHE cosmic rays.](image-url)
crease the sensitivity by as much as two orders of magnitude [11].

EVA’s novel approach makes use of toroidal radio reflector/concentrator optics that are integral to the superpressure balloon itself. A ~ 10 – 12 m high reflective equatorial band on the outer balloon membrane forms a powered toroidal radio-frequency mirror, with a focus inside the balloon, about halfway between the center and the portion that is reflecting. The optics are such that the balloon can receive radio impulses from any direction near the horizon, covering a very large synoptically viewed area of 1-2M square kilometers. At the focal zone inside the balloon, a membrane is suspended containing a feed antenna array which receives the power from the focusing optics. Fig. 8 shows a cutaway view of the basic geometry of the system. The light blue band represents the reflector band, and the red band in the interior is the feed antenna support. This finite element model had only a small number of gores; in practice the 18MCF full-scale version will have 280 gores.

EVA’s optics must be stable and smooth enough to avoid degrading reflected RF signals up to frequencies of several hundred MHz; this is only possible using a SPB, since the overpressure maintains a stable surface profile. Physical optics simulations and exact microwave scale models have confirmed that the optics perform well at the required radio wavelengths, and a 1/10 to 1/5-scale demonstration balloon is expected to be fabricated sometime in 2014. If the approach is validated and the technology readiness level can be raised, EVA can be expected to be a contender for a near-future Small Explorer Mission of Opportunity.

4.3. Pathways to (and from) Space instruments.

The success of the CREAM payload has now led to selection of a CREAM follow-on for the International Space Station (ISS), given the acronym ISS-CREAM (pronounced like the ice-cold dessert). Because of the extended mission now given the ISS, engendered by the continuing support for the Alpha Magnetic Spectrometer, ISS-CREAM will allow an upgraded version of the CREAM instrument to gather much higher statistics needed to resolve the behavior of the cosmic ray spectrum at the knee. ISS-CREAM is expected to be launched in 2014.

In a twist, a mission planned for many years for the ISS, the Japanese Experiment Module Extreme Universe Space Observatory (JEM-EUSO), which is slated to be lifted to the ISS late this decade, will first validate some of its required measurements using a balloon payload. JEM-EUSO uses a very large Fresnel-lens and associated fast camera to image the optical fluorescence emission from UHE cosmic ray air showers transiting the atmosphere below it, from an altitude of 350 km on the ISS. By careful timing of the arrival of the fluorescence pulse, JEM-EUSO can determine the arrival direction of the primary particles, and by integrating the received light, establish their energy. JEM-EUSO will be the first UHE cosmic ray observatory in space, but to ensure that the measurements can be made with the requisite accuracy, the EUSO-Balloon mission will attempt three flights in the 2014-2016 time frame with an
instrument which will allow an end-to-end test of JEM-EUSO’s key technologies.

Finally we note that ANITA’s discovery that a balloon payload could successfully observe ultra-high energy cosmic rays has generated interest in extending this method of observation to a space-based platform, where the acceptance could be large enough to greatly extend the reach compared to even the largest ground-based observatories, providing a method that is highly complementary to the approach used by JEM-EUSO.

The Synoptic Wideband Orbiting Radio Detector (SWORD) satellite mission, now under development at NASA’s Jet Propulsion Lab, is a new concept based on ANITA’s results [12], and shown in concept in Fig. 9. SWORD will fly a deployable interferometric antenna array covering the 30-300 MHz range, lower than that used by ANITA, but more tuned to the largest amplitude radio emission from UHE cosmic rays. SWORD observes UHECRs through the reflection of the impulsive beamed radio emission off the Earth’s surface, whether ocean, land, or ice. Challenges faced by SWORD will be calibration of the reflective surface for each event, along with deconvolution of the ionospheric effects, which are quite strong, especially at the low end of SWORD’s frequency range.

SWORD is planned as a low-cost SMEX mission, but could achieve sensitivity of nearly two orders of magnitude compared to ground-based observatories, particularly in the super-GZK energy range, above $10^{20}$ eV, where little is known about the endpoint behavior, and the sources should become more evident due to the much lower deflection by intergalactic magnetic fields. SWORD is planned to fly at the next solar minimum, roughly 2019.

In the interim, ANITA will fly again in 2014, and should measure several hundred more radio-detected UHECRs. This will go a long way toward refining the radio emission models that are necessary to more precisely calibrate the response of instruments like SWORD, and it is likely that an ANITA-IV instrument will be proposed for the Antarctic LDB program, with a specific goal of measuring even more such events.

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